

# International Geology Review

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## IGR transliteration of Russian

The AGI Translation Office has adopted the essential features of Cyrillic transliteration recommended by the U. S. Department of the Interior, Board on Geographical Names. Washington D. C.

However, the AGI Translation Office recommends the following modifications:

1. Ye initially, after vowels, and after *ъ, ь*. Customary usage calls for "ie" in many names, e. g., SOVIET KIEV, DNEPER, etc.; or "ye", e. g., BYELORUSSIA, where "e" follows consonants. "e" with dieresis in Russian should be given as "yo".
2. Omitted if preceding a "y", for example, Arkhangelsky (not "iy"; not "ii").
3. Generally omitted.

NOTE: Well-known place and personal names that have wide acceptance will be used. Some translations may include elements of previous German transliteration from the Russian; this occurs in IGR most commonly in maps and lists of references. The reader's attention is called to the following variations between German and English systems which may cause confusion when trying to check back to original Russian sources.

Alphabet	transliteration	
А	а	a
Б	б	b
В	в	v
Г	г	g
Д	д	d
Е	е	e, ye <sup>(1)</sup>
Ё	ё	ë, yë
Ж	ж	zh
З	з	z
И	и	i <sup>(2)</sup>
Й	й	y
К	к	k
Л	л	l
М	м	m
Н	н	n
О	о	o
П	п	p
Р	р	r
С	с	s
Т	т	t
У	у	u
Ф	ф	f
Х	х	kh
Ц	ц	ts
Ч	ч	ch
Ш	ш	sh
Щ	щ	shch
Ъ	ъ	" <sup>(3)</sup>
Ы	ы	y
Ь	ь	' <sup>(3)</sup>
Э	э	e
Ю	ю	yu
Я	я	ya

German	English
w	v
s	z
ch	kh
tz	ts
tsch	ch
sch	sh
schtsch	shch
ja	ya
ju	yu

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# LIQUID INCLUSIONS IN MINERALS AS A GEOLOGIC BAROMETER<sup>1</sup>

by

V. A. Kalyuzhnyy<sup>2</sup>

• translated by V. P. Sokoloff •

## ABSTRACT

The understanding and determination of pressures at the time of mineral formation is an important factor in the study of mineral-forming environments; environmental pressures are derived through investigation of physicochemical properties of gaseous-liquid inclusions. The pressure-temperature (P-T) diagram for H<sub>2</sub>O with specific-volume isograds, is used as a basis of computation. Complex CO<sub>2</sub>-inclusion samples for experimentation were taken from quartz crystals found in the Nogolnyy range (Donbass). A basic premise of pressure estimation involved ascertaining that conditions were identical for capture of both CO<sub>2</sub> and H<sub>2</sub>O phases by minerals from a system in its heterogeneous state. The capture process may have involved adhesion of CO<sub>2</sub> bubbles to crystal faces as carbonic acid moved (as an emulsion) with the mother liquors. Two types of syngenetic inclusion are investigated: Homogeneous inclusions consisting of aqueous, or gaseous, solution of 'pure' carbonic acid were used for temperature determinations; and homogeneous inclusions, for pressure determinations. The latter required estimation of specific weight (specific volume) for inclusion contents at the time of inclusion sealing. Complex relationships of included matter with respect to liquid and gaseous phase-volume ratios to aqueous-solution content and to solubility of carbonic acid in water and of H<sub>2</sub>O in CO<sub>2</sub>, necessitated careful compensation for error throughout the investigation. Inclusion cavity volumes were expressed as two hexagonal pyramids plus one prism; and liquid carbonic-acid and gas-bubble inclusion volumes, as spheres standard for the computation of actual volumes for deformed gas bubbles. The author describes a method and apparatus for measurement of gaseous-bubble volumes and for transfer of included materials to determine deformation effects on gaseous-liquid inclusion volumes. Dimensions of gaseous bubbles are compared to those of ideal geometric figures. It was found that gaseous bubbles up to 0.4 mm in diameter were not deformed, i. e. spherical and those 0.4 to 2.0 mm in diameter approached the shape of an ellipsoid of rotation; in this case, 10 percent reduction in volume was introduced as compensation for error. Pressure calculated for Volynian pegmatites at the time of crack healing in morion, was based on two, largely gaseous, inclusions. Pressures established for the time of mineral formation were a minimum of 222 atmospheres for the first sample, and 292 atmospheres for the second. --D. D. Fisher.

Pressure is among the most important factors determining mineral formation. Detailed studies on properties of liquid inclusions in minerals enable us to ascertain, with varying degrees of reliability, the physicochemical environment surrounding mineral formation. Particularly, these studies serve to guide further improvement in methods of geological barometry.

It is known, that accuracy of measurements on mineral-formation temperature by homogenization of liquid inclusions, depends significantly on considerations of the former initial pressure. In turn, this pressure cannot be determined to sufficient accuracy without knowledge of the environmental temperature of mineral formation. At the moment of their

homogenization, the state of inclusion is characteristics of certain temperature-pressure minima of the natural processes. By knowing the exact magnitude of one factor, we can determine the magnitude of the second with a fair degree of reliability. Close interdependence of the two principal variables (T and P), however, appears to form an unbroken, closed circle. Although this circle is more apparent than real, in a number of instances, it may be unlocked by consideration of the actual conditions surrounding hydrothermal or pneumatolytic mineral formation.

The P-T diagrams (which, in reality, become the P-T-V diagrams on addition of the specific volume curves) serve as the most satisfactory premises for objective discussion on possibilities of determining principal factors in mineral formation. The P-T diagram for H<sub>2</sub>O is suited especially for establishment of general rule.

Studies of the properties of aqueous inclusions in minerals show, by the P-T Diagram (fig. 1) that slight changes in temperature cause major changes in pressure within the liquid-phase range (the isochors are inclined

<sup>1</sup>Translated from *Zhivkiye vkluycheniya v mineralakh kak geologicheskyy barometr*: Lvovskogo Geologicheskogo Obshchestva Mineralogicheskyy Sbornik, no. 9, p. 64-84, 1955.

<sup>2</sup>Ivan Franko State University, Lvov.



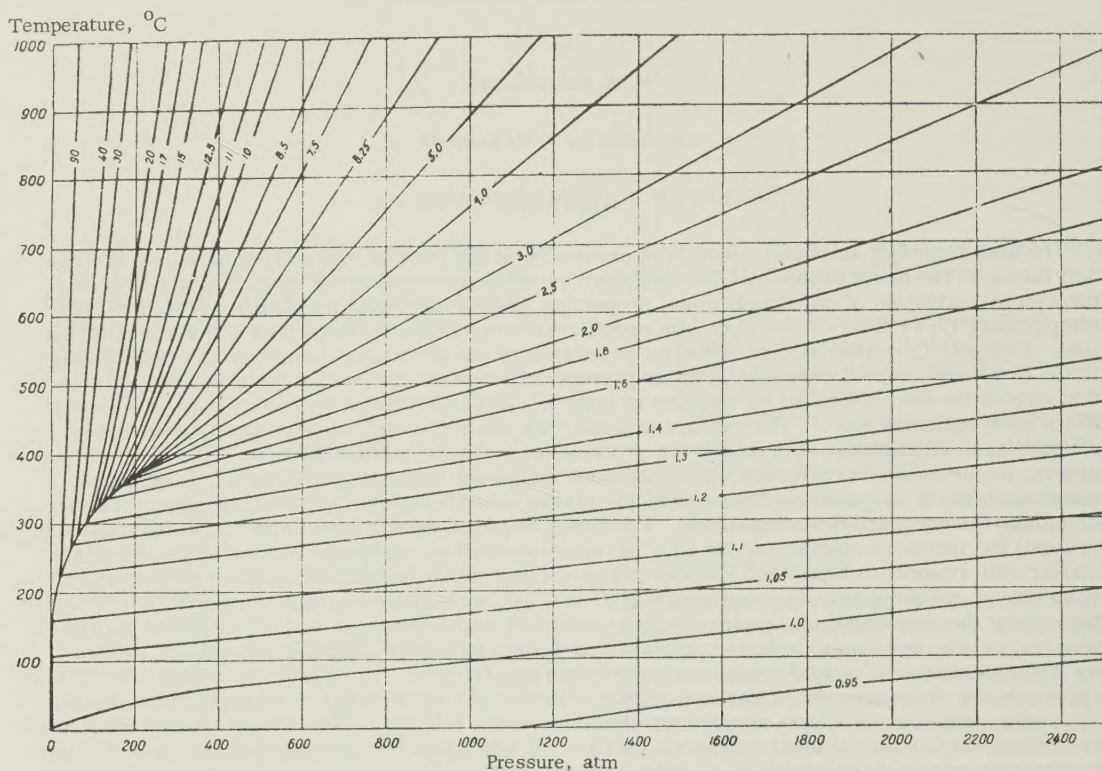


FIGURE 1. The P-T diagram with specific-volume isograds, according to Kennedy [14] and others [1]

weakly toward the pressure axis). Within the gaseous-phase range, however, we are dealing with the opposite type of dependence between prominent factors (the isochors forming large angles incident to the P axis [Tr: The author uses "axis" for "abscissa" or "ordinate", the latter two terms are as standard in Russian as they are in English. VPS]. Hence, diagram [Tr.: physical?]) states is subdivided, depending on the suitability of liquid or gaseous inclusions as a means of pressure and temperature determination.

Inclusions having low specific volumes are conserved at relatively high pressures and low temperatures. Such inclusions may be used for estimation of mineral-formation temperature but in practice, are not suitable for use as geological barometers. Inclusions with high specific volumes, which originated, chiefly from gaseous solutions, at high temperatures and relatively low pressures, may serve for estimation of pressures but are practically unsuitable for use as geological thermometers. For intermediate specific volumes, near critical volumes, both the possibilities and precision of measurements occupy intermediate positions.

The foregoing premises are fundamental to

mineralogical thermometry; and, as well, they help to simplify the complexity of the [Tr.: physical] state of liquid inclusions. Chemical composition of inclusions is highly significant; their chemical [Tr.: "Khimism," in the original, like the German "Chemismus." Both terms are obscure to us. According to context, the term can mean "features," "chemical environment," "composition," "reactions," or even "chemical history of the system in question." VPS.] features are especially important to the estimation of pressures. This is made clear even by the fact that we can appraise solution densities, in the case of the liquid inclusions, by reference to the density of water; analogies of this sort do not hold for gaseous inclusions. Gaseous-inclusion density may differ in the extreme from the saturated-vapor density of an aqueous solution; [Tr.: "nasyschennogo para vodnogo rastvora," literally: "of the saturated vapor of an aqueous solution." The author has in mind a confined gas-liquid system at equilibrium. VPS] this was attested by Davy's experiments on inclusions [11]: the included gaseous bubble increased twelve-fold after the inclusions had been cut open under water. [Tr.: In the original: "exposed in an aqueous medium." VPS].

Inclusions of "pure" carbonic acid [5],



complex CO<sub>2</sub> inclusions (aqueous solution and liquid carbonic acid-gas) [Tr.: Whether "liquid H<sub>2</sub>CO<sub>3</sub>" in the sense of meaning liquid CO<sub>2</sub> or, of an aqueous solution of CO<sub>2</sub> is intended is not known. VPS], and gaseous inclusions may be employed for estimation of pressures. G. G. Grushkin [2] made an attempt based on liquid-gaseous inclusions, to determine pressures in N. P. Yermakov's terminology.

At the homogenization moment, pressures of carbonic acid within inclusions, correspond to the minimal and scarcely plausible values of P and T (up to their critical values of 70 atm and 31.4°C, respectively). This fact was considered by Johnsen [13] who suggested a way to determine pressures with the aid of carbonic acid inclusions; he was unable to estimate the pressures, however, because he did not know the mineral-formation temperatures. Holden [12] used complex inclusions that could be homogenized into the liquid phase. His determinations cannot be considered satisfactory inasmuch as the results he obtained were appreciably lower than for pressures inside inclusions at the time of their homogenization; the latter circumstance is a consequence of his having neglected changes in the specific volume of carbonic acid in the course of homogenization.

S. A. Chaykovsky's method of determining pressures is analogous to that of Holden: His employment of the complex gaseous inclusions with liquid CO<sub>2</sub> could have led to more reliable results, but, unfortunately, Chaykovsky had failed to consider partial pressure for saturated vapor of the aqueous phase at the homogenization moment, as well as of the filling-up of inclusions, under surficial conditions. By first approximation, assuming partial pressure of 87 atm for pure water of 300°C, one could make Chaykovsky's measurements more exact: 131 plus 87 equals 218 atm. The effect of volume occupied by the aqueous solution at room temperature is insignificant, amounting to an 8-10 atm decrease, if the filling-up is about 10 percent.

Grushkin's method of determining the pressures [2] is based on the difference between the experimental homogenization temperature of natural inclusions and the temperature of their filling, computed from volume expansion for pure water. Since the inclusions contain solutions and gaseous components other than, and in addition to, water vapor, the calculated homogenization temperature is invariably lower than the experimental temperature. Having estimated pressure required for the decrease in water volume by the magnitude corresponding to the difference between the two temperatures, the author can find the minimum pressure value operative during mineral formation.

The pressure estimated by Grushkin cor-

responds to that within the inclusion at the moment of its homogenization, with allowance for pressures of the gaseous components. In general, this result does correspond to a certain minimum pressure for the mineral-forming environment. However, the method in question appears to have chiefly theoretical significance for the following reasons:

a) Exact measurements of the phase volumes (tenths and hundredths of one percent) required by the method are at this writing unattainable in practice, especially if we consider the form of the inclusion in fluorites; b) For inclusions with low specific volumes, insignificant temperature anomalies may lead to errors, actually overlapping established differences between pressures for three generations of fluorite (240, 425, and 620 atm).

Investigation into the possibility of determining mineral-formation pressures, based on complex inclusions of CO<sub>2</sub> and the fundamentally gaseous inclusions, are reported in the present paper.

#### Chapter I

As formerly [5], pressures were estimated using CO<sub>2</sub> inclusions in quartz crystals from the Nagolnyy Range (Donbass). The basic premise of the estimates, by the method employed, involved establishment of the fact that conditions were identical for capture of the two phases, H<sub>2</sub>O and CO<sub>2</sub>, by the mineral from a system in its heterogeneous state.

This was done by a detailed and diligent study of the syngenetic liquid inclusions in our factual materials.

With respect to the origin of such heterogeneous and separate solutions, we follow the opinion of V. A. Nikolayev, to the effect that distillation and condensation of the gaseous phase undergoing a separation from the magmatic melt are extended. "... over a certain temperature range and the range of the pressures, in the course of variations in the composition of the gaseous and the liquid phases. Individual components of the gaseous mixture, e. g. CO<sub>2</sub>, may remain in the gaseous state, while they dissolve partially in the condensing solution to the point of its saturation, or, they become liberated from the solution into the gaseous phase on decrease in the external pressure; for example, during the ascending movement of solutions or, in the fissures of the containing rock" [8; p. 104].

We suppose that a similar process of gaseous-phase separation with decrease in solubility, was taking place during ore deposition in the veins of the Nagolnyy Range. The carbonic acid so liberated, as an emulsion, was moving together with the mother liquor.



Minerals formed in such environment could capture carbonic-acid bubbles at the faces of their crystals. The mechanism of such capture may be visualized in the scheme of Nacken [15]. Inclusions forming from the fractionated ore-depositing solution, at the time of their sealing shown in Figures 2 and 3, may be:

- (a) Homogeneous (we shall refer to them from now on as inclusions of homogeneous origin), consisting of a liquid aqueous solution or of gas (inclusions of "pure" carbonic acid);
- (b) Heterogeneous (inclusions of heterogeneous origin).



FIGURE 2. Syngenetic complex inclusions of  $\text{CO}_2$ . 134.5x

- (a)  $\text{CO}_2$  inclusion of homogeneous origin.
- (b)  $\text{H}_2\text{O}$  inclusion of homogeneous origin.
- (c) Inclusions of heterogeneous origin.
- (d) Inclusions of heterogeneous origin with two gas bubbles.

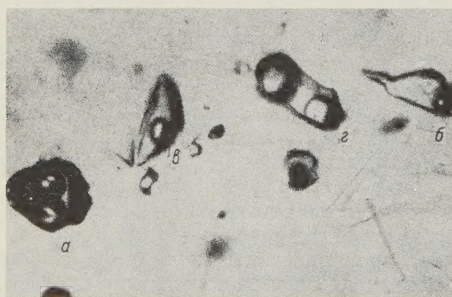


FIGURE 3. Same as Figure 2, but with more concentrated illumination (with "LAZO" lens introduced). 134.5x

Only the homogeneous inclusions of an aqueous solution are suited for temperature determinations. Other inclusions, syngenetic with the first, may be used in measurement of pressure, the second principal determinant of mineral formation. Depending on the type of inclusions selected, of those containing car-

bonic acid at the time of their capture, there may be two methods of pressure measurement based on the homogeneous or the heterogeneous  $\text{CO}_2$  inclusions. The limits of applicability for these two methods are defined conventionally, even as inclusions themselves are differentiated conventionally because the captured homogeneous phase contains generally a certain proportion of liquid aqueous solution.

Homogeneous inclusions of  $\text{CO}_2$  or  $\text{H}_2\text{O}$  may contain greater or lesser proportions of the components ( $\text{H}_2\text{O}$  or  $\text{CO}_2$ ), respectively, under surficial conditions, in view of certain peculiarities of the binary system with limited miscibility of  $\text{H}_2\text{O}$  and  $\text{CO}_2$ .

Determination of pressures by inclusions containing maximum quantities of carbonic acid is less complicated and more reliable than the method using inclusions of  $\text{CO}_2$  of heterogeneous origin. However, the theoretical premises of the second method, presently to be discussed, have more general validity; they include premises of the first method, a simplified special case, of pressure determination using "pure"  $\text{CO}_2$  inclusions.

The principal objective of the given method is estimation of specific weight (or specific volume) of carbonic acid at the time of the inclusion sealing. By comparison of heterogeneous and homogeneous syngenetic inclusions and on the basis of certain experimental data for the  $\text{H}_2\text{O}-\text{CO}_2$  system, it should be possible to eliminate fully effects of the aqueous solution captured by the inclusion together with the gas bubble, at the time of inclusion sealing. This problem may be solved by evaluation of the following basic factors affecting the calculations:

1. Solubility of carbonic acid in water during mineral formation and, under equilibrium conditions within the inclusion, at room temperature. The evaluation is carried out by comparing inclusions of heterogeneous and homogeneous ( $\text{H}_2\text{O}$ ) origin.
2. Solubility of  $\text{H}_2\text{O}$  in  $\text{CO}_2$  at room temperature. According to Laurie and Ericson [As cited in the Russian version of Johns and Quinn [3]. VPS. ], this solubility is less than 0.05 percent and is of no practical consequence.
3. Solubility of  $\text{H}_2\text{O}$  in  $\text{CO}_2$  in the mineral-forming environment. In the absence of data on solubility of water in carbonic acid at high pressures and temperatures, it is not possible to make exact estimates of the specific volume of  $\text{CO}_2$  at the time of its capture and sealing, although certain experimental data allow us to estimate the order of magnitudes of  $\text{H}_2\text{O}$  concentration in  $\text{CO}_2$ . Thus, the minimum quantities of aqueous solution in the complex inclusions investigated [5] constitute 2 to 5 percent; this indicates the probable upper limit of the



magnitude studied, because by all appearances, part of the solution in the inclusion was captured at the time of sealing of the CO<sub>2</sub> bubble, all other factors notwithstanding. Moreover, according to R. F. Sukhorskii [10], an inclusion containing up to 15 percent liquid carbonic acid and 5 percent of the aqueous solution, becomes homogeneous at 220°C, that is, 5 percent H<sub>2</sub>O may be dissolved in the gaseous solution of the given composition, at 220°C. By comparing the homogenization curve of a regular tabular inclusion in a quartz crystal from Ostry Bugor, containing 56 percent carbonic acid and 44 percent aqueous solution at 13°C, with the theoretical curves derived for pure water, we obtain about 2 percent liquid water, as vapor in the gaseous solution of carbonic acid at 200°C. Consequently, from the data here cited, and in view of the close resemblance in chemical composition of the inclusions in question to the tubular inclusion here mentioned, we assume that concentration of water vapor in gaseous carbonic acid solution of low specific volume to be 3± 1 percent at 200°C.

4. Concentration of the aqueous solution in the mineral-forming environment, with respect to the host-mineral substance and to the easily soluble salts (it appears that the first has but slight effect, although exact appraisal is impossible, in the absence of pertinent data, while the second has insignificant magnitude, as shown by the closeness of refraction indices of the inclusions to those of pure water).

In this manner, using appropriate corrections, it is possible to reduce a complex inclusion to the relatively simple case of the inclusion of carbonic acid of homogeneous origin.

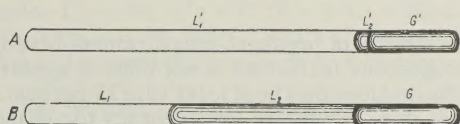


FIGURE 4. Schematic view of complex CO<sub>2</sub> inclusions of homogeneous (A) and heterogeneous, (B) origin. L<sub>1</sub> and L<sub>1</sub>', L<sub>2</sub> and L<sub>2</sub>', and G and G' are the respective volumes of aqueous solution, liquid carbonic acid, and gas

Let us assume that the mineral contains two regular tabular inclusions (fig. 4): A is an H<sub>2</sub>O inclusion of homogeneous origin and B, an inclusion of heterogeneous origin (complex), conforming to criteria of syngenetic origin from heterogeneous solution. Their volume ratios for the aqueous solution, the liquid carbonic acid, and the gas are:

L<sub>1</sub> : L<sub>2</sub> : G' and L<sub>1</sub>' : L<sub>2</sub>' : G, respectively.

Accordingly, the volume of carbonic acid under mineral-formation conditions (W<sub>CO<sub>2</sub></sub>) [16]

[Tr: (cM2')] in original is a misprint; this expression is, in reality, (W<sub>CO<sub>2</sub></sub>). The author uses lower case Russian letters as superscripts on p. 71 of original et seq.: "zh" "g"; the initials for "liquid" and "gas", respectively. These are replaced by corresponding initials "l" and "g" for equivalent words in English. VPS.] may be derived, with the aid of appropriate corrections, from the volume of liquid carbonic acid L<sub>2</sub>, and of the gas G, present in the surficial environment, as follows:

1. Reduction in the volume L<sub>2</sub> + G, to correct for thermal contraction of the aqueous solution L<sub>2</sub> [Tr.: The L<sub>2</sub> in Figure 4 refers to the liquid carbonic-acid volume (not of the aqueous solution). VPS.], in proportion to the reduction in the volume of the aqueous solution in Inclusion A:

$$\frac{L'}{L'_2 + G'} = \frac{L_1}{\Delta v'}, (-\Delta v') = \frac{L_1(L'_2 + G')}{L'_1}$$

2. Reduction in the liquid carbonic-acid volume L<sub>2</sub>, and increase in the gas volume G, due to the solubility in water of carbonic acid, in the mineral-forming environment, corresponding to the amount of carbonic acid L<sub>2</sub>' and G' in Inclusion A.

(a) The CO<sub>2</sub> content of the volume G', on conversion to its liquid-state volume is:

$$\Delta L'_2 = \frac{G' d^g_{CO_2}}{d^l_{CO_2}}$$

where d<sup>g</sup><sub>CO<sub>2</sub></sub> is density of CO<sub>2</sub> in the gaseous phase; and d<sup>l</sup><sub>CO<sub>2</sub></sub> its density in the liquid phase.

(b) The volume changes L<sub>2</sub> + G (± Δv'')

$$\frac{L'}{L'_2 + \Delta L'_2} = \frac{L_1}{\Delta v''}; (\pm \Delta v'') = \frac{L_1(L'_2 + \Delta L'_2)}{L'_1};$$

while Δv'' does not change the total volume L<sub>2</sub> + G, it affects the total mass of CO<sub>2</sub> [Ed.: carbonic acid(?)] in the given volume.

3. An increase in volume L<sub>2</sub> + G due to the solubility of H<sub>2</sub>O in CO<sub>2</sub> (ΔL<sub>1</sub>) in the mineral-forming environments:

$$(+\Delta v''') = \frac{\Delta L_1(L_2 + G)}{100}$$

However, our corrections are only approximate: By the first approximation, we assume the observed phase volumes to be the same as they were in the mineral-forming environment. All three corrections must be recalculated, for greater accuracy, by introduction of appropriate changes corresponding to the values, Δv', Δv'', and Δv'''



previously obtained. The results shall have, then, the following, respective expressions:

$$\begin{aligned}\Delta v_1 &= \frac{(L_1 + \Delta v' - \Delta v''') (L'_2 + G')}{L'_1}; \\ \Delta v_2 &= \frac{(L_1 + \Delta v' - \Delta v''') (L'_2 + \Delta L'_2)}{L'_1}; \\ \Delta v_3 &= \frac{\Delta L_1 (L_2 + G - \Delta v' + \Delta v''')}{100}.\end{aligned}$$

The two successive estimates of the corrections are entirely adequate for the purpose, in the calculations carried down to the first decimal. We had verified this in practice.

Estimates of carbonic-acid density in mineral-formation may be made as follows:

1. Carbonic-acid volume of the heterogeneous inclusions, in the mineral-forming environments:

$$W_{CO_2} = L_2 + G - \Delta v_1 + \Delta v_3$$

2. Carbonic-acid mass:

$$M_{CO_2} = (L_2 - \Delta v_2) d^L_{CO_2} + G d^G_{CO_2}$$

3.  $CO_2$  density at the (P-T) of mineral formation:

$$d_{CO_2} = M_{CO_2} : W_{CO_2}.$$

Making use of the combined  $CO_2$  -  $H_2O$  (P-T) diagram for [5; fig. 2], we find the isochor corresponding to the density  $CO_2$  estimated. As in the determination of P by homogeneous inclusions of carbonic acid, intersection of the isochors for  $CO_2$  and for aqueous syngenetic inclusion yields both temperature and pressure not far removed from those at the moment of capture of inclusions by the given mineral. The partial pressure of water vapor dissolved in carbonic acid at mineral-formation temperature must be added to the figure obtained from the diagram.

If homogenization of carbonic acid (partial homogenization of the inclusion) takes place in the liquid phase (in practice generally true), calculations of  $CO_2$  density ( $d_{CO_2}$ ) are best performed in a different manner. Specifically, after determination of  $CO_2$  volume at the time of inclusions sealing,

$$W_{CO_2} = L_2 - \Delta v_1 + \Delta v_3 \quad (\text{as } G = 0)$$

and of mass for liquid carbonic acid,  $M_{CO_2} = (L_2 - \Delta v_2) d^L_{CO_2} + G d^G_{CO_2} = (L_2 - \Delta v_2) d^L_{CO_2}$  to find the density:

$$d_{CO_2} = \frac{(L_2 - \Delta v_2) d^L_{CO_2}}{L_2 - \Delta v_1 + \Delta v_3}. \quad (I)$$

One should remember that phase-volume ratios in both inclusions must be measured at the temperature of gaseous-phase disappearance in the heterogeneous inclusion B. The sequence of calculations of  $d_{CO_2}$  here offered makes it unnecessary to determine volume ratios for the liquid carbonic acid and gaseous bubble in the complex inclusion.

At relatively low pressures, there may develop complex inclusions whose entire liquid carbonic-acid content may pass into the gaseous phase on heating (partial homogenization in the gaseous phase). Under such conditions, it is clear that liquid carbonic acid in a syngenetic  $H_2O$  inclusion of homogeneous origin will pass into the gaseous phase some time before the required temperature is attained for partial homogenization of the complex inclusion. In such cases, measurement of the phase ratios in both inclusions should be made at condensation temperature for carbonic acid in the homogeneous  $H_2O$  inclusion. The  $\Delta v_3$  correction may be made in the manner previously discussed; for the other corrections:

$$\Delta v_1 = \Delta v_2 = \frac{(L_1 + \Delta v' - \Delta v''') (L'_2 + G')}{L'_1},$$

if we express  $CO_2$  solubility in  $H_2O$ , at the time of inclusion sealing  $\Delta v_2$ , is expressed in terms of its volume in the gaseous state.

The general expression for  $CO_2$  density in the mineral-forming environment becomes, then, as follows:

$$d_{CO_2} = \frac{L_2 d^L_{CO_2} + (G - \Delta v_2) d^G_{CO_2}}{L_2 + G - \Delta v_1 + \Delta v_3}. \quad (II)$$

Reliability of pressure measurement based on heterogeneous inclusions is not high; it appears that digressions may be at least 10 to 15 percent. This is due, chiefly, to low accuracy for phase ratios in the inclusions. Errors in liquid- $CO_2$  and gas determinations tend especially to affect results for homogeneous inclusions. In such instances, accuracy of measurements may be regarded as satisfactory, if the errors do not exceed one percent of total volume of the inclusion.

Digressions due to inexact volume measurements of aqueous solutions are less important. They may become insignificant, if we choose complex inclusions with the least percentages of aqueous solution. The limit of such selection is inclusions of "pure" carbonic acid; and, from the fundamental expression (I) becomes:

$$d_{CO_2} = \frac{L_2}{L_2 + \Delta L_1} d^L_{CO_2}, \quad (III)$$

$$\Delta v_1 = \Delta v_2 = 0 \quad G' \text{ и } \Delta v_3 = \frac{\Delta L_1 (100 + 0)}{100} = \Delta L_1.$$

These aqueous solution effects have the



following explanation: The volume expression,  $L_1$ , for aqueous solutions of heterogeneous inclusions enters the formulae for  $\Delta v_1$  and  $\Delta v_2$ . If the latter are stated as:

$$\Delta v_1 = \frac{L_1}{L'_1} G' ; \Delta v_2 = \frac{L_1}{L'_1} (L'_2 + \Delta L'_2),$$

it becomes clear that  $\Delta v_1$  and  $\Delta v_2$  vary in the same direction as any change in their common factor  $\frac{L_1}{L'_1}$ . At the same time,  $\Delta v_2$  enters the

numerator and  $\Delta v_1$ , the denominator of equation (1), with the same signs. On proper selection of complex inclusions with low aqueous-solution content (e. g. up to 30 percent), the value for  $L_2$ , in both the numerator and the denominator of the equation, become relatively high (90 to 70 percent). Concurrently,  $\Delta v_2$  and  $\Delta v_1$  are expressed in mere units, [Tr.: YEDINITSA is "one", 1; in the plural, the meaning is ambiguous. In the literary usage, of e. g. Pushkin, the meaning of the plural would be  $\Delta v_2$  and  $\Delta v_1$  equal unity. However, the author seems to imply the low order of magnitude which is also good and common usage. VPS.] as a consequence of general range of the method's applicability (the hydrothermal mineral formation at temperatures lower than 320 to 300°C). Errors in measurements of  $\Delta v_2$  and  $\Delta v_1$  have but small influence; accordingly, on relationships stated in the terminal equation; and, consequently, on the very results of the measurements. Simple calculations show, e. g. for the phase ratios, in the homogeneous and heterogeneous inclusions, respectively:

$L'_1 = 90$ ,  $L'_2 = 4$ ,  $G' = 6$ ;  $L_1 = 30$ ,  $L_2 = 70$ , and  $d_{CO_2} = 0.97 d'_{CO_2}$ . The filling changes in  $L_2$ , to the extent of 20 to 30 percent, yield the same result as formerly. In a somewhat different phase ratio:  $L'_1 = 90$ ,  $L'_2 = 7$ ,  $G' = 3$ ;  $L_1 = 20$ ,  $L_2 = 80$ ,  $d_{CO_2} = 0.96 d'_{CO_2}$ , and a 15 percent deviation in  $L_1$  gives  $d_{CO_2} = (0.96 \pm 0.01) d'_{CO_2}$ .

Let us consider now an example of pressure determination by heterogeneous inclusions. Three inclusions in "negative form" with different phase ratios were discovered, alongside some others, within a healed crack of a quartz crystal from Ostry Bugor (figs. 5 and 6). On

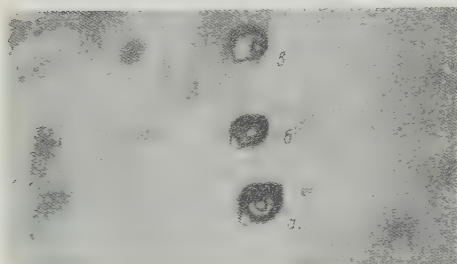


FIGURE 5. Complex CO<sub>2</sub> inclusions at 15°C. 250x

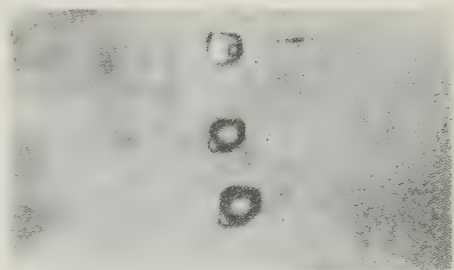


FIGURE 6. Same inclusions as in Figure 5 at 25°C. 250x

cooling the section, the light ray directed by the introduced "Lazo" [Tr.: As transliterated from Russian; the original spelling need be reestablished VPS.] lens (for the detection of carbonic-acid inclusions non-transparent in the ordinary microscopic illumination, we recommend always that the Lazo lens be used), was used to establish that each of two inclusions contained a small gas bubble and, in approximately equal proportions, aqueous solutions and liquid carbonic acid. The third inclusion was formed, apparently, by sealing of an homogeneous aqueous solution.

Having assumed each of the inclusion cavity volumes to be expressed by the sum of two hexagonal pyramids and one prism, and the liquid carbonic-acid and gas-bubble volumes to be spheres, we calculated the phase ratio in complex inclusions, at the vanishing temperature of the gas bubble.

**Inclusion a.**  $L_2$ , the liquid carbonic-acid content equals 50 percent, by our calculations.

The temperature of disappearance of the gaseous phase is 21.0°C.

Area of the prism base and pyramid =  $0.5 \pi R^2 \sin \alpha = (0.5) 6 \times 15^2 \cdot \sin 60^\circ = 584.6 \text{ units}^2$ . Prism volume =  $Sh = 584.6 \times 12 = 7015.2 \text{ units}^3$ . Volume of the pyramids =  $1/3 Sh = (584.6) 15 = 2929 \text{ units}^3$ . Total cavity volumes =  $7015.2 + 2 (2929) = 12861 \text{ units}^3$ . Liquid CO<sub>2</sub> volume =  $1/6 \pi d^3 = \frac{3.14 (23)^3}{6} = 6367.4 \text{ units}$ .

**Inclusion b.** For the gaseous phase, the vanishing temperature is 23.2°C. Area of prism base is  $0.5 (6) (12.5)^2 (0.866) \text{ or } 405.9 \text{ units}^2$ . [Tr.: Yedinits", abbreviated Yed.: units (unspecified). VPS.] Prism volume =  $405.9 (10) \text{ or } 4059 \text{ units}^3$ . Pyramid volume =  $1/3 (405.9) (12) \text{ or } 1623.6 \text{ units}^3$ . Total inclusion-cavity volume =  $4059 + 1623.6 (2) \text{ or } 7306 \text{ units}^3$ . Liquid-CO<sub>2</sub> volume =  $\frac{3.14 (20)^3}{6}$

or 4186.7 units<sup>3</sup>. L<sub>2</sub>, the liquid carbonic acid-content of the inclusions, is 57 percent.

**Inclusion c.** Area of the prism base = 0.5 (6) (14)<sup>2</sup> (0.866) = 509.2 units<sup>2</sup>. Prism volume = 509.2 (2) = 1018.4 units<sup>3</sup>. Pyramid volume = 1/3 x 509.2 (14) = 2376.3 units<sup>3</sup>. Total inclusion-cavity volume = 1018.4 + 2376.3 (2) = 5771 units<sup>3</sup>. Gas-bubble and liquid carbonic-acid volume = 1/6 (3.14) (9)<sup>3</sup> = 381.5 units<sup>3</sup>. At 21°C the gas bubble had volume = 1/6 (3.14) (8)<sup>3</sup> or 267.9 units<sup>3</sup>. At 23°C there were practically no noticeable changes in the gas-liquid phase ratio of CO<sub>2</sub>, possibly because of poor visibility. Thus, at 21° to 23°C, the phase ratio in the inclusion was:

$$L' : L' : G' = 93 : 2 : 5.$$

Temperature of complete homogenization of the inclusion in the liquid phase was 145°C.

Calculation of Pressure by Inclusions a and c:

- 1)  $93 : 7 = 50 : \Delta v'$ ;  $\Delta v' = 50 (7) : 93 = 3.8$ ;
- 2)  $\Delta L'_2 = G' d^3_{CO_2} : d^4_{CO_2} = 5(0.199) : 0.755 = 1.3$ ;  $L'_1 : (L'_2 + \Delta L'_2) = L_1 : \Delta v''$ ,  $\Delta v'' = 3.3(50) : 93 = 1.8$ ;
- 3)  $50 : 100 = \Delta v''' : \Delta L_1$ ,  $\Delta v''' = (50)3 : 100 = 1.5$  ( $\Delta L_1 = 3$  percent, by assumption).

The second elaboration of the corrections:

- 1)  $\Delta v_1 = 52.3(7) : 93 = 3.9$ ;
- 2)  $\Delta v_2 = 3.3 (52.3) : 93 = 1.9$ ;
- 3)  $\Delta v_3 = 47.7 (3) : 100 = 1.4$ .

By equation (1):

$$d_{CO_2} = \frac{50 - 1.9}{50 - 3.9 + 1.4} \cdot (0.755) = 0.76 \text{ g/cm}^3$$

By diagram [5, fig. 2], the sealing environment for inclusions a and c corresponds to 195°C temperature; the pressure (with the correction for partial pressure of water vapor inside the volume of gaseous CO<sub>2</sub> at the given temperature) is 800 + 14 = 814 atm<sup>2</sup>.

Calculation of Pressure by Inclusions b and c:

- 1)  $L'_1 : G' = L_1 : \Delta v'$ ,  $\Delta v' = 43 (7) : 93 = 3.2$ ;
- 2)  $\Delta L'_2 = 5(0.199)(0.755) = 1.3$ ;  $\Delta v'' = 3.3 (43) : 93 = 1.5$ ;
- 3)  $57 : 100 = \Delta v''' : 3$ ,  $\Delta v''' = 57 (3) : 100 = 1.7$ .

The second elaboration of the corrections:

- 1)  $\Delta v_1 = 44.5 (7) : 93 = 3.4$ ;
- 2)  $\Delta v_2 = 44.5 (3.3) : 93 = 1.6$ ;
- 3)  $\Delta v_3 = 55.5 (3) : 100 = 1.7$ .

$$d_{CO_2} = \frac{57 - 1.6}{57 - 3.4 + 1.7} \cdot (0.731) = 0.73 \text{ g/cm}^3$$

The environment of origin of the inclusions b and c, by the diagram and the calculation, was at 192°C and 730 + 13 = 743 atm. pressure.

Thus our determinations of the healing conditions for one crack, on the basis of two inclusions, differ from each other by 7°C and 110 atm pressure. Lack of agreement probably results from shortcomings of the method employed.

We have made one more attempt to determine pressure of mineral formation, by heterogeneous inclusions found also in a quartz crystal from Ostry Hugor. This group of heterophase inclusions is shown at different temperatures in the photomicrographs (figs. 7 and 8). The pictures

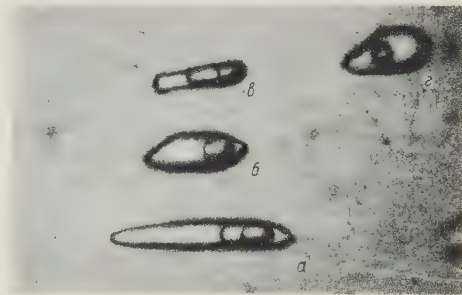


FIGURE 7. Complex inclusions of CO<sub>2</sub> at 15°C. 250x

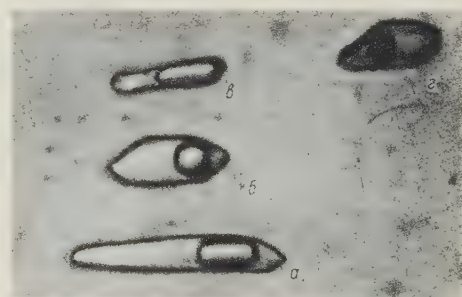


FIGURE 8. Same inclusions as in Figure 7, at 25°C. 316.6x

were taken with the introduced LAZO lens). All inclusions were assumed to be syngenetic. Inclusions b, c, and d were selected for the measurements. Two of them, b and d, were believed to be homogeneous (although their phase ratios proved to be rather dissimilar); the third, a complex inclusion, was thought to be heterogeneous.



At the vanishing temperature of the gas bubble in the complex inclusion (13°C), the following phase ratios were observed:

Inclusion b —  $L'_1 : L'_2 : G' = 90 : 8 : 2$ ;

Inclusion c —  $L_1 : L_2 = 30 : 70$ ;

Inclusion d —  $L'_1 : L'_2 : G' = 95 : 2 : 3$ .

The homogenization temperature for d and b proved to be 154°C and 220°C respectively, by the first type.

Estimates of mineral-forming environments, in the sequence previously followed, gave the results:

1. By inclusions b and c

$$\Delta v_1 = 3.5; \Delta v_2 = 2.9; \Delta v_3 = 2.1.$$

$$\rho_{\text{CO}_2} = \frac{70 - 2.9}{70 - 3.5 + 2.1} (0.831) = 0.81 \text{ g/cm}^3;$$

$$t = 330^\circ, P = 1700 \text{ atm.}$$

2. By inclusions c and d

$$\Delta v_1 = 1.6; \Delta v_2 = 0.8, \Delta v_3 = 2.1.$$

$$\rho_{\text{CO}_2} = \frac{70 - 0.8}{70 - 1.6 + 2.1} (0.831) = 0.81 \text{ g/cm}^3;$$

$$t = 208^\circ, P = 1016 \text{ atm.}$$

Comparison of the results obtained shows  $\text{CO}_2$  densities, computed on the basis of really quite different inclusions, to be identical. The large difference in pressure is due to the significant difference in homogenization temperature of b and d. It seems that both temperature and pressure calculated from d are closer to reality. The excessively high homogenization temperature of c may result from capture of some carbonic acid along with the aqueous solution.

To compare results obtained by two different methods based on  $\text{CO}_2$  inclusions, for estimation of pressure, mineral-formation P-T data are presented (table 1) for the "pure"  $\text{CO}_2$  inclusions in quartz crystals from Ostry Bugor (partial pressure of the aqueous solution  $\Delta P$  is taken into consideration).

The temperature-pressure relationship for the fundamentally gaseous inclusions, after their homogenization, is reflected in the P-T diagram by the corresponding curves of specific volume isograds (isochers) tending to follow the temperature axis but strikingly inclined with respect to the pressure axis (fig. 1). The homogenization point represents also certain environmental minima in mineral-formation for the given inclusions. Although such a minimum is not acceptable even as the crudest aid in the estimation of temperatures, it may not be far from reality in our estimations of pressures. By making use of certain geologic data, it is possible to establish certain limits for range of pressures at the time of mineral-formation. The upper limit for quartz-formation temperature may be taken as 700°C, i. e. the temperature of beginning of the pegmatitic stage, according to Fersman. One may utilize the alpha to beta ( $\alpha - \beta$ ) transition point of quartz, as fixed by the so-called "honeycomb" inclusions in healed cracks developing, in certain instances, upon abrupt volume contraction; for example, in the Volynian pegmatites.

Pressure may be calculated in accordance with certain laws of thermodynamics for either real or ideal gases, based on essentially gaseous inclusions. If qualitative composition of the gaseous phase has been established, it is possible to apply the van der Waals equations. Our determinations are based on interdependence of P, T, and V for ideal gases.

Pressure within inclusions may be higher or lower than atmospheric pressure, depending on content of their gaseous components. We have observed occasionally, upon opening inclusions in dehydrated glycerine, sucking of glycerine by the inclusion and abrupt 5- to 10-fold decrease in gaseous bubble volume. On the other hand, pressure within inclusions often exceeds atmospheric pressure. In some of our experiments, gaseous-bubble volume increased 40 to 100 times.

Let us assume pressure, volume and tempera-

TABLE 1. Determinations of pressure based on homogenetic  $\text{CO}_2$  inclusions

Number	Vanishing Temperature of Gas Bubble in $\text{CO}_2$ inclusions °C	Homogenization temperature of syngenetic "aqueous" inclusions °C	Density of $\text{CO}_2$ at inclusions sealing g/cm <sup>3</sup>	Results			
				Temperature °C	Pressure (atm)		
					P	$\Delta P$	Total
1	19	142	0.753	188	750	12	762
2	20	144	0.744	188	710	12	722
3	20	130	0.743	168	650	7	657
4	16	137	0.780	185	810	11	821
5	16	137	0.780	185	810	11	821

ture within the inclusion in surficial environment and at its homogenization moment, to be represented by  $P_1$ ,  $W_1$ ,  $T_1$  and  $P_2$ ,  $W_2$ ,  $T_2$ , respectively. On opening the inclusion, its gaseous phase is to be characterized by  $P_3$ ,  $W_3$ , and  $T_3$ .

An expression for an ideal gas may be given as:

$$Pv = BT,$$

where  $P$  is pressure;  
 $v$  specific volume;  
 $B$  gas constant; and  
 $T$  absolute temperature.

For an inclusion exposed at temperature  $T_1$ , and liberated gaseous phase at  $T_3 = T_1$ , the equations of state will be:

$$P_1 v_1 = BT_1; \quad P_3 v_3 = BT_1,$$

[Tr.: In the original:  $B_3 v_3 = BT_1$  a misprint. VPS]

After an easy simplification, we have:

$$P_1 = \frac{P_3 v_3}{v_1}.$$

Multiplying the right side of the equation by  $M$ , mass of the gas, we have:

$$P_1 = \frac{P_3 W_3}{W_1}. \quad (1)$$

For a gram-molecule of gas within a sealed inclusion, the equation of state may be given as:

$$V = \frac{RT_1}{P_1}, \quad (2)$$

where  $V$  is the gram-molecular volume of gas. [Tr.:  $R$  is the gas constant. VPS. Ed.: Gas constant given first as  $B$ ; probably a misprint.]

Pressure within the inclusion at the temperature of its homogeneous state is:

$$P_2 = \frac{RT_2}{V}. \quad (3)$$

After the appropriate substitutions for  $P_1$  and  $V$ , in equations (2) and (3), we have:

$$P_2 = \frac{T_2 W_3 P_3}{T_1 W_1}.$$

The value for  $P_3$  may be taken at 1 atm for the surficial environment. The  $W_3 W_1$  ratio indicates increase in gaseous-phase volume of the inclusion, on liberation.

Pressure so obtained need be augmented by partial pressure of water vapor which develops at the expense of solution within the inclusion. At homogenization temperature, this partial pressure may be determined from the tables or from the PT nomogram for the saturated state.

Partial pressure for temperatures above the homogeneous state, may be found from isochors

of the PT nomogram for water. Of course, such corrections were merely approximate; they do not take into account concentrations of volatile and nonvolatile components.

Insofar as possible, the larger inclusions were selected for our determinations. One may add that, in Volynian pegmatite minerals, fundamentally gaseous inclusions 2 to 4 mm in diameter are common practically in any crystals. For exact volume measurements, the mineral specimen is polished into a prism or a cube to afford the possibility of its measurement, sketching, and photography in two or more mutually perpendicular planes. Inclusion volume is approximated, generally, to the volume of the regular figures [Tr.: i.e. geometrical figures or their sums, as evidenced by the examples of the calculations. VPS.] Volume measurement error is probably + 10 to 15 percent, depending on complexity of the cavity's configuration. Upon estimation of its volume, the inclusion is heated to its homogeneous state.

Inclusions are opened in dehydrated glycerine, a highly suitable liquid for retention of the liberated gas [7; p. 292]. The preparation is attached to the slide with Canadian balsam (fig. 9), then

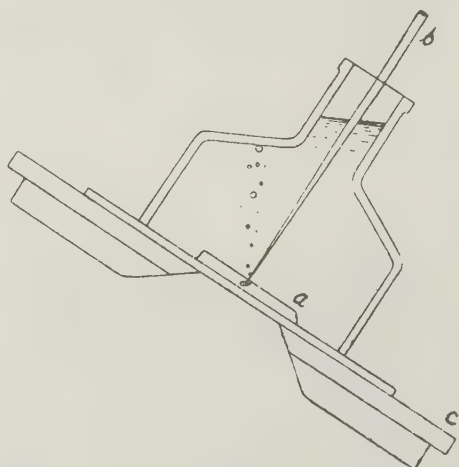


FIGURE 9. A vessel for capturing the liberated gaseous phase of the inclusions. Actual size.

(a) section of mineral containing inclusions; (b) tip of the microdrill; (c) microscope stage.

covered by a glass vessel of special design. This vessel is made by cutting off the bottom of a suitable jar and polishing the cut surface. The vessel is glued to the slide with balsam and then filled with glycerine. This device is placed in an inclined position on the microscope stage to prevent liberated bubbles from entering the jar neck and to force them under the horizontal portion of the jar wall. The wall



separating the inclusion and the thin-section surface (polished down to minimum thickness) is broken by using a microdrill or a Pobedite [Tr.: Transliteration; an alloy. Its composition is not given. VPS]. needle.

Volume of the liberated gas bubbles is calculated from their diameter, measured by the micrometer. If the intercepting wall is regularly flat, measurements can be made directly; i. e. in the same vessel. Otherwise, the bubbles must be transferred to an especially designed measuring cuvette (fig. 10). The cuvette [Tr.: The apparatus in Figure 10 is referred to, in the original, first as cuvette, then as "measuring bath", etc. The glass slide under which the bubbles are collected is called "intercepting wall", "slide", or "glass plate", or retaining plate" etc. For the sake of clarity, these terms are translated consistently as "cuvette" and "intercepting plate". VPS.]

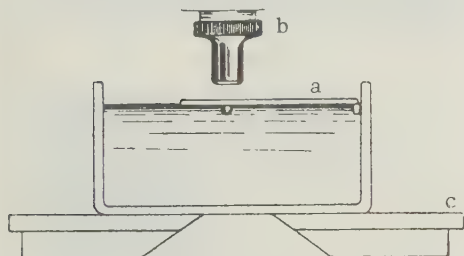


FIGURE 10. Measuring cuvette. Actual size. (a) intercepting wall; (b) microscope ocular; (c) microscope stage.

consists of a glass bath and an intercepting glass plate. The lower surface of the plate is polished to minimize the gaseous-bubble mobility. The plate is placed horizontally, supported by two other glass plates glued with Canadian balsam.

Gaseous bubbles are transferred to the cuvette with the Polyakova's micropipette [3], a fine capillary leading to a sequence of 2 or 3 separate reservoirs (fig. 11).



FIGURE 11. Polyakova micropipette.

First, glycerine alone is sucked into the micropipette, to fill the first two reservoirs. Next, gaseous bubbles are sucked in, together with more glycerine. The gaseous bubbles are placed under the intercepting plate of the glycerine-filled cuvette by blowing them out of the pipette. However, gaseous-bubble volume under the intercepting plate in glycerine, is not

a sphere. The bubble is somewhat deformed, approximating an ellipsoid of rotation. The diameter, measured by the method described, is the major axis of the ellipsoid. Volumes estimated by the mensuration formula for a sphere are thus, greater.

Using, a cuvette with horizontal side-walls, we endeavored to ascertain approximately the deformation effects on volume measurements of gas bubbles, as spheres, as seen through the microscope (above). On placing air bubbles into the cuvette, we measured micrometrically the minor ( $d_1$ ) and the major ( $d_2$ ) axes of the ellipsoid, through the tube of a horizontally placed microscope. The results are shown in Table 2.

Table 2. Volume measurements of gaseous bubbles

Number	Gaseous-bubble size (mm)		Gaseous-bubble volume (mm <sup>3</sup> )	
	$d_1$	$d_2$	Sphere volume <sup>1</sup>	Ellipsoid volume <sup>2</sup>
1	0.44	0.45	0.048	0.047
2	0.52	0.52	0.074	0.074
3	0.74	0.76	0.230	0.224
4	0.74	0.78	0.249	0.236
5	0.82	0.90	0.382	0.348
6	0.96	1.06	0.624	0.565
7	1.08	1.16	0.818	0.762
8	1.40	1.52	1.840	1.695
9	1.64	1.86	3.372	2.973
10	2.17	2.67	9.974	8.106
11	2.42	2.09	15.460	12.108
12	2.42	3.13	16.068	12.423

$$V = -1/2 - \pi d_2^3 \quad V = 1/6 - \pi d_1, d_2^2$$

Comparison of results obtained shows that bubbles up to 0.4 mm in diameter remain undeformed, for all practical purposes; and, may be assumed to be spheres, within the limits of reliability for our measurements. Volume of bubbles with diameter  $d_2$  of 0.4 to 2.0 mm is greater than the actual volume (here assumed equal to that of an ellipsoid of rotation) by about 10 percent. Accordingly, it is necessary to subtract 10 percent from the volume of these bubbles, computed on the assumption that their shape is spherical. It is best not to work with bubbles exceeding 2 mm in diameter; since their deformation may be so great as to render the assumption that their form is ellipsoidal inconsistent with the accuracy required for estimations. Large gaseous bubbles must be broken into small ones; e. g., with a needle.

Volume of gaseous bubbles may be calculated directly from the mensuration formula for an ellipsoid, if we establish graphically, on the basis of our data, the relationship between  $d_1$  and  $d_2$ . Both methods give practically identical errors.

Accuracy of volume measurements by this

method, e. g. for  $d_2 = 1.86$  mm, assuming error in measurement of the gaseous-bubble diameter to be  $\Delta d_2 = \pm 0.02$  mm, will be:  
[Tr: There seems to be an ambiguity here, due possibly to incorrect punctuation; the following equations seem rational but the first one seems oddly placed and the plus-minus signs do not seem to follow from the equations. VPS.]

$$V = 1/6\pi d_1 d_2^2 \frac{\Delta V_0}{V_0} = \frac{0.02}{1.64} + 2 \frac{0.02}{1.86} =$$

$$\pm 0.034 \text{ or } \pm 3.4 \text{ percent;}$$

$$V_0 = 0.034 (3.30) = \pm 0.102 \text{ mm}^3$$

We attempted to determine of pressures for some Volynian pegmatites at the time of crack-healing in morion, based on two fundamentally gaseous inclusions. Samples were collected at two different sites.

First Sample. The inclusion is shown in three projections (figs. 12, 13, 14). On cooling,



12



13



14

FIGURES 12, 13 and 14. An essentially gaseous inclusion in morion (VOLYN); projected on three mutually perpendicular planes. 63.5x

we observed liquid carbonic acid to pass entirely into the gaseous phase at 24°C. The proportion of aqueous solution was about 5 per cent. Total cavity volume was assumed to be that of a prism:

$$V = Sh = (0.55) (0.19) (1.09) = 0.11 \text{ mm}^3$$

The gaseous-phase volume was determined after opening, to be the sum of volumes for six bubbles formed in the glycerine; results are shown in Table 3.

Inclusion-cavity volume must be added to the volume obtained; because at 1 atm pressure ( $11.30 + 0.11 = 11.41 \text{ mm}^3$ ), part of the gaseous phase could not escape through the drilled opening.

Consequently, the gaseous-phase volume after opening the inclusion, was 103.7 times as great as the cavity volume ( $W_3: W_1 = 11.46: 0.11 = 103.7$ ). Thus, at room temperature (25°C) there existed pressure, within the inclusion, corresponding approximately to 104 atm



TABLE 3. Gaseous-phase volume of opened inclusion and measurement errors\*

Number	Gaseous-bubble diameter	Volume of bubbles	Correction (-10%)	Gaseous-phase volume of inclusion	Relative error of measurements (%)
	mm	mm <sup>3</sup>		mm <sup>3</sup>	
1	1.54	1.91	0.19	1.72	3.1
2	0.81	0.28	0.03	0.25	7.1
3	1.28	3.48	0.35	3.13	0.5
4	1.93	3.77	0.38	3.39	0.5
5	0.72	0.19	0.02	0.17	10.5
6	1.80	3.05	0.31	2.64	0.6

$$*V = 1/6\pi r^3 d^3$$

taking into account the fact that such pressure could not have been produced by the vapor of carbonic acid alone; because, at the time of CO<sub>2</sub> condensation (24 percent) in our inclusion pressure could be only 62 atm, we must assume that some other gases were present in the inclusion.

At homogenization temperature, pressure within the inclusion resulting from the gaseous phase was equal to:

$$P_2 = \frac{T_2}{T_1} \left( \frac{W_1}{W_2} \right) P_3 =$$

$$\left( \frac{252 + 273}{25 + 273} \right) \times \left( \frac{11.41}{0.11} \right) (1) = 183 \text{ atm.}$$

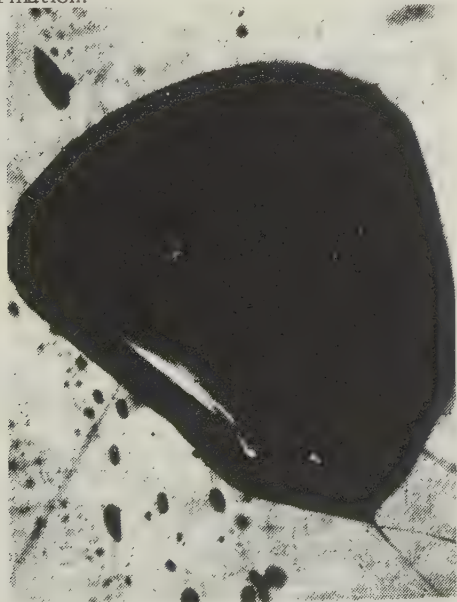
The total pressure, including the partial pressure of water vapor, was:

$$P = 183 + 39 = 222 \text{ atm.}$$

The value of P here obtained corresponds to the minimum pressure at the time of mineral formation.



16



15



17

FIGURES 15, 16, and 17. A chief gaseous inclusion in mdrion (VOLYN'); projected on three mutually perpendicular planes. 28.4x

If we take 600°C as the upper temperature limit ("honeycomb" inclusions were absent in the crystals under investigation), the possible maximum pressure will be:

$$P_2 = \left( \frac{600 + 273}{25 - 273} \right) \times (103.7) = 304 \text{ atm.}$$

$P = 304 + 125 = 429 \text{ atm}$ , where the partial pressure of water vapor was found at a point with the ordinate of 252°C, consistent with PT dependence on an isochor diverging from the phase-equilibrium curve. [Ed.: My interpretation, original not clear.]

Let us estimate now, as an example, the order of magnitude of measurement errors. Assuming the reliability measurements for volume inclusion cavity, to be + 15 percent, or 0.017 mm<sup>3</sup>, and the average error in measurements of gaseous-bubble volume to be 3.7 percent (table 3), the relative error is:

$$\frac{\Delta P_2}{P_2} = \pm \left( \frac{\Delta T_2}{T_2} + \frac{\Delta W_3}{W_3} + \frac{\Delta T_1}{T_1} + \frac{\Delta W_1}{W_1} \right) =$$

$$\pm \left( \frac{5}{525} + \frac{0.40}{11.41} + \frac{0.5}{298} + \frac{0.017}{0.11} \right) = \pm 0.197,$$

or  $\pm 19.7\%$ .

The absolute error is:

$$\Delta P_2 = \pm P_2 (0.197) = \pm 183(0.197) = \pm 36 \text{ atm};$$

$$P = 222 \pm 36 \text{ atm.}$$

At the upper pressure limit (at 600°C), the order of reliability is about the same:

$$P = 429 \pm 80 \text{ atm.}$$

Second sample. The inclusion in morion (figs. 15, 16, 17), together with its syngenetic inclusions, was cooled to  $\pm 6^\circ\text{C}$ . The second liquid phase was not detected in any of the inclusions. Volume of the inclusion in question was taken to be that of a cylinder:

$$V = \pi r^2 h = (3.14) (0.75^2) (0.63) = 1.12 \text{ mm}^3.$$

The total volume of the liberated gaseous phase was 42.66 mm<sup>3</sup>.

Homogenization of the inclusion took place at 310°C in the gaseous phase. Partial pressure of the gas within the inclusion, at 310°C temperature, was:

$$P_2 = \left( \frac{583}{298} \right) \left( \frac{42.66}{1.12} \right) = (1.96) (38.09) = 75 \text{ atm.}$$

The total pressure at 310°C was

$$P = 75 + 98 = 173 \text{ atm.}$$

At 600°C,

$$P_2 = \left( \frac{873}{298} \right) (38.09) = 112 \text{ atm};$$

$$P = 112 + 180 = 292 \text{ atm.}$$

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# PETROCHEMICAL STUDY OF THE CENOZOIC BASALTIC ROCKS IN EASTERN CHINA<sup>1</sup> (PART 1 OF 2)

by  
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• translated by E. C. T. Chao •

## ABSTRACT

Cenozoic basalt lavas are widely distributed in the coastal region and adjacent districts in eastern China. They form either widespread plateaus or scattered mesas; and, in some places, the volcanic craters are well preserved. These basalt sheets were erupted from multiple vents in the late Tertiary and early Quaternary.

The results of a petrochemical study of the Cenozoic basalt in eastern China are given. The most characteristic feature of the more basaltic rocks is their high  $K_2O$  content, also the under-saturation in silica. In North China and South Manchuria most basalts are trachybasalts and occasional nepheline basalt. The constituent minerals of these basalts are anorthoclase, potash-adesine, plagioclase, titanite, and abundant olivine. In South China the main basalt is olivine basalt, consisting of olivine, augite, and plagioclase. At some places the basalt may be slightly silica saturated and the occasional presence of hypersthene and quartz (xenocryst) is noteworthy. In North Manchuria the dominant basalt is leucite basalt, containing leucite and olivine as phenocryst and ground-mass constituents. Xenocrysts of quartz and feldspar are sometimes present. In Taiwan Province, the basalt of Kuan-yin-shan (volcano) is of the tholeiite type, but, in some other districts, the alkaline basalt with feldspathoidal constituent also occurs.

The petrographical difference seems to be matched by the differences of the major tectonic forms of China. These facts are tabulated as follows:

Geographical regions	Tectonic forms	Basalt type
1. North Manchuria	Granitized region in Variscide	Leucite basalt
2. North China and South Manchuria	Precambrian Sino-Korean massive	Trachybasalt
3. South China	Huanan platform in Yenshanide	Olivine basalt
4. Taiwan	Himalayide	Tholeiite basalt

--- from "General Sketch" of author's English Resumé

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## INTRODUCTION

The distribution of the Cenozoic volcanic rocks in eastern China is fairly widespread. They extend from Heilungkiang province in the north to Hainan Island in the south. They crop out in the coastal provinces of, Kirin, Liaoning, Hopei, Shantung, Kiangsu, Chekiang, Fukien, Taiwan, Kwangtung and adjoining areas. They occur as vast igneous tablelands such as in the Tun-hua and Mu-leng area of the Northeast [1] and Hanorpa of the Chang-pei area [2]; or they form isolated buttes such as the lower reaches of the Yangtze River near Nanking and Liu-ho [3], and Ch'i-hsia and T'ang-shan of Shantung province [4]. Furthermore, in many areas where recent basalts occur, traces of volcanic necks and craters are still preserved; for example, they can be clearly observed at T'ien-ch'ih of Pai-t'ou-shan of Kirin province [5], at the Ta-erh-po of Inner Mongolia [6], at Jü-shan of Yü-i, Kiangsu [7], and at Kao-shan-t'ai Wan-chuan [2] etc. areas.

De Chardin [8] described the distribution, occurrence and the age of eruption of the Cenozoic volcanic rocks of China. Yin Tsan-hsün [9] described the distribution and the structure and types of Recent volcanoes in China. Such descriptions will not be repeated here. In general, the mode of extrusion of most of the basalts of eastern China is of the multi-vent regional type, equivalent to the plateau basalt type of Tyrrell (1932) [10] and not the fissure eruption type. Most of the eruptions occurred between late Eocene and Pliocene, continued in Pleistocene and diminished in the Recent. Descriptions of basalts are dispersed throughout foreign and domestic geological literature, including many important contributions. The description, discovery and studies of Chinese Cenozoic basaltic rocks are briefly listed chronologically as follows:

1. In 1908, A. Lanick [11] discovered the nepheline basalt of Yan-shan of Wei-hsien in Shantung province.

2. In 1912, B. Koto [12] discovered the nepheline basalt of Ts'ao-shih, near Ying-o-men of Ch'ing-yuan of Liaoning province.

3. In 1928 and 1929, [Tr. : In original, 1927 and 1928. Numerous errors appear in the citation of references in the text, tables,

and bibliography. Wherever possible, corrections have been made based on a check of the original document cited. Where the original is not readily available, the reference citation in the text was made to agree with the reference as cited in the bibliography.] A. Lacroix [13, 14] described the silica-saturated basalts of Inner Mongolia and eastern Manchuria and their associated undersaturated limburgite, basanitoid, and mancharite (a nepheline basalt) etc; Lacroix also pointed out that the basalts of the Mu-leng area of eastern Manchuria are especially rich in potash.

4. In 1932 and 1933, T. Tomita [15, 16] described the basalts of Pai-t'ou-shan of Chang-pei in Kirin and of Hsueh-hua-shan of Ching-ching in Hopei province as olivine, labradorite trachyandesitic basalt with potash-bearing andesine plagioclase in the groundmass. Subsequently, in 1933, S. Seto [17] described the basalts of Wei-ch'ang, and Ling-yuan of Jehol province as also of this type.

5. In 1934, Yeh Liang-fu and Yü teh-yuan [18] described the olivine basalts of Fang-shan between Nanking and Chen-chiang. The groundmass feldspars are andesine which chemically contain more than the normal amounts of  $K_2O$ .

6. In 1936, T. Ogura [19, 20, 21, 22] discovered the alkali basalt of Te-tu, Wu-yun and Erh-tung-chi volcanoes (Wu-ta-lien-ch'ih) of Heilungkiang province. Because the rock contains leucite and relatively abundant plagioclase it is called shihlunite [shihlungite]. Subsequently in 1938 and 1939 he described the leucite basanite of Erh-k'e-shan of K'e-tung in Heilungkiang province and the leucite basalt of Ch'i-hsin-shan of Shuang-liao of Liaoning province.

7. In 1929, 1943 and 1947, T. Ichimura [23, 24, 25] described the leucite basanite of Hsin-chu of Formosa, and the olivine-pyroxene basalt, hypersthene basalt and quartz olivine basalt etc. of Hainan Island.

8. In 1948, Chen Yü-ch'i and Shen Yung-ho [26] studied the basalts of Fang-shan near Nanking. They described in detail the rocks, their chemical composition, the structure of the volcano. and its history.

9. In 1949, Yen Ts'ang-po [27] described

the alkali basalt of Hsin-chu of Formosa which contains leucite, orthoclase and biotite.

10. In 1949, A. Harumoto [28] described the nepheline basalt of Ch'i-hsia and T'ang-shan of Shantung province.

11. In 1950, T. Ichimura [29] described the olivine-pyroxene basalt and its differentiate pyroxene-amphibole andesite of Kuan-yin-shan from Formosa.

12. In 1951, Shen Yung-ho [30, 31, 32] described the basalts of She-wu-shan, near Ch'ih-shan of Nanking, and of Chu-t'ou-shan of P'u-chen.

In addition, S. Kozu and others in 1922 [33] described the glassy alkalic lava rock and the alkalic trachyte of Pai-t'ou-shan. Later, because the alkalic trachyte contains a rather high amount of silica and high alumina, B. Yamanari in 1928 [34] named it paitouite. As mentioned by De Chardin, Pai-t'ou-shan is the only area where Cenozoic acid volcanic rocks are observed.

From this, it can be seen that the basaltic rocks of eastern China consist of a complex suite of rocks consisting of olivine basalt, hypersthene basalt, quartz basalt, trachybasalt, nepheline basalt, leucite basalt, and glassy pyroxene-olivine basalts. These rocks are distributed within certain areas. As to the chemistry of these rocks, except those basalts from Inner Mongolia and Manchuria discussed by A. Lacroix [13], no summary or systematic study is available. In assembling the data on the volcanic rocks of China, the author has collected about 70 chemical analyses of basalts. As compared with basalts of other parts of the world, the Cenozoic basalts of eastern China have the same world-wide characteristics with respect to their petrography, chemical composition, magma type and origin. The complexity of rock types, and the wide range of variation of mineral and chemical composition of the rocks of this area, are, however, rarely found elsewhere in the world. The variation of their composition apparently is directly and closely related to the geotectonic units. The parent basalt magma is also the most alkalic of the world.

## REGIONAL COMPARISONS

### Comparison of Chemical Composition

The distribution of the Cenozoic basalts of eastern China is shown in Figure 1. This map is reduced from the general geological map of China (scale 1:3,000,000) compiled by the Geologic Committee in 1951. The original map divided the basalts of the northeast into 3 periods of extrusion which are omitted here. Numbers on the map indicate localities of samples that

have been chemically analyzed. The list of localities is given in the footnote of table 2A. Up to 1951 about 70 analyses appeared in the literature. These are arranged in chronological order in Table 1.

As mentioned above, the chemical composition of the basalts of eastern China shows distinct variation. A wide range of variation [of percent composition of constituent oxides] may be noted from Table 1, for example:

SiO <sub>2</sub>	41.13 - 55.51
Al <sub>2</sub> O <sub>3</sub>	8.67 - 21.54
Fe <sub>2</sub> O <sub>3</sub>	0.89 - 10.97
FeO	1.30 - 9.95
MgO	1.68 - 15.42
CaO	5.47 - 11.19
Na <sub>2</sub> O	1.27 - 5.22
K <sub>2</sub> O	0.50 - 5.76
TiO <sub>2</sub>	0.34 - 4.16

Among such variations, those of northern Manchuria are higher in K<sub>2</sub>O such as no. 3 (near Nen-chiang) which contains up to 5.76 percent. Those of southern Manchuria and northern China are higher in Na<sub>2</sub>O, for example no. 36 (Hsueh-hua shan of Hopei) and no. 37 (T'ang-shan-t'ou of Shantung) contains as much as 5.07 percent to 5.22 percent Na<sub>2</sub>O. Those of Formosa are high in alumina. No. 66 from Kuang-yin-shan of Tan-shui has 21.54 percent Al<sub>2</sub>O<sub>3</sub>. The basalts of Hainan Island contain more silica. No. 59 from T'an-k'ou has 55.51 percent SiO<sub>2</sub>. The mineral composition as related to the chemical composition also shows regional variation which seems to be closely related to the geotectonic units. As mentioned above, the northern Manchurian area corresponds to T. K. Huang's [38] Palao-Asiatic type of Variscan fold-fault zone and the northern Manchuria granite region, where many outcrops of leucite basalt occur. Northern China and southern Manchuria correspond to the Precambrian Sino-Korean crystalline massif. Here the basalts are mostly coarse-grained with some associated nepheline basalt. The basalts of southern China which includes the Yen-shan folds, the Yangtze platform, and the Caledonian folded belt of Cathaysia, or what is called by V. M. Senechin [40] the southern Chinese massif, are largely olivine-bearing. The Taiwan region belongs to the Himalayan folded belt. It is thus clear that chemically and mineralogically the basaltic rocks of eastern China show notable regional characteristics. These are described as follows:

### Southern China

The region includes the vicinity of Nanking and Hainan Island. The basaltic rocks of this region are relatively high in silica. More than



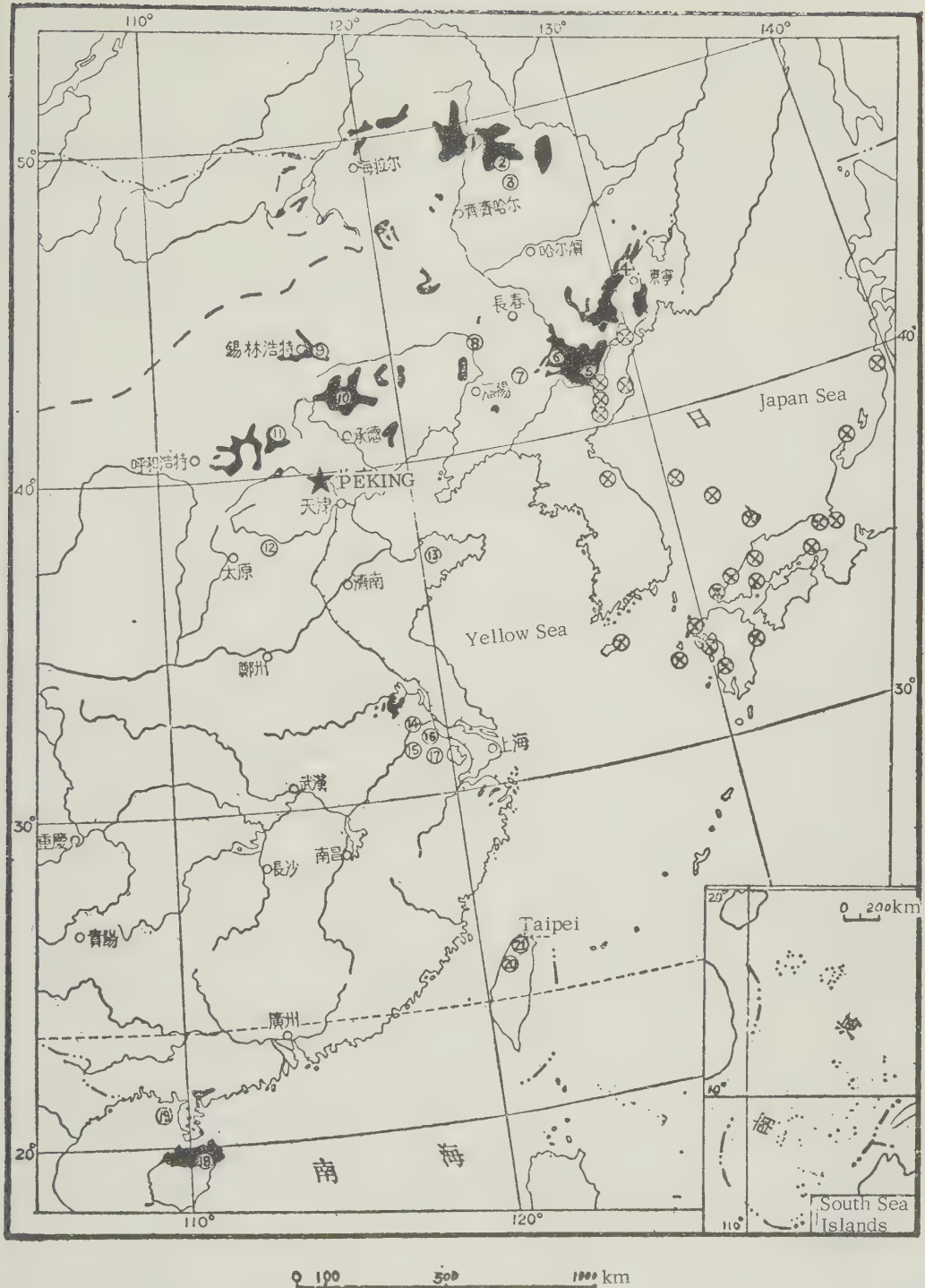


FIGURE 1. Map showing the distribution of the Cenozoic basalts of eastern China

① - ⑳ location of samples of the Cenozoic basalts of eastern China.

⊗ location of samples of alkalic rocks of the Circum-Japan Sea region.

# INTERNATIONAL GEOLOGY REVIEW

TABLE 1. The chemical composition of the Cenozoic basaltic rocks of eastern China

No.	Rock type <sup>1</sup>	Locality	Reference
1	Holocrystalline lava rock	Near Nen-chiang Heilungkiang	Zavaritsky [35]
2	Glassy lava rock		
3	Plagioclase, leucite shihlungite		
4	Leucite shihlungite	Northern part of Te-tu, Heilungkiang	T. Ogura et al [19]
5	Trachybasalt		
6	Non-leucite shihlungite		
7	Anorthoclase olivine basalt		
8	Residual lava rock		
9	Leucite basanite	Erk-k'e-shan of K'e-tung, Heilungkiang	T. Ogura [20]
10	Vesicular lava rock		
11	Basanitoid	Muleng, Heilungkiang	A. Lacroix [13]
12	Limburgite		
13	Basanitoid basalt		
14	Andesine basalt		
15	Analcite tephritoid		
16	Andesine basalt	Pai-t'ou-shan of Ch'ang-pai, Kirin	A. Lacroix [14]
17	Basic lava rock	Lung-wan of Ching-yu, Kirin	T. Ogura [36]
18	Nepheline basalt	Yin-o-men of Ch'ing-yuan, Liaoning	B. Koto [12]
19	Leucite olivine basalt	Ch'i-hsin-shan of Hsuang-liao, Liaoning	T. Ogura [21]
20	Trachybasalt		
21	Andesine basalt	Wei-ch'ang, Hopei	A. Lacroix [13]
22	Pegmatitic basalt		
23	Andesine basalt		
24	Limburgite	Northwest of Ta-erh-po, Inner Mongolia	
25	Andesine basalt		
26	Basanitoid	Shen-wei-t'ai of Wan-ch'uan, Hopei	
27	Basanitoid	Shan-fang-pao of Wan-sh'uan, Hopei	
28	Labradorite basalt	Hanorpa of Wan-ch'uan, Hopei	
29	Andesine basalt		
30	Trachybasalt	Hsueh-hua-shan of Ching-ching, Hopei	T. Tomita [16]
31	Nepheline basalt	T'ang-shan, Ch'i-hsia, Shantung	A. Harumoto [28]
32	Limburgite	T'ai-shan, Shantung	A. Lacroix [13]
33		Fang-shan of Chiang-ning, Kiangsu	Chen Yu-chi and others [26]
34	Olivine basalt		
35	Coarse-grained basalt		
36	Porphyritic basalt		



# CHAO TSUNG-PU

including some andesites, trachytes and alkalic rocks.

SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	H <sub>2</sub> O (+)	H <sub>2</sub> O (-)	Other	Total	No.
42.84	2.49	12.13	5.86	4.43	0.17	11.80	10.44	2.37	3.68	0.55	3.44	...	0.18	100.38	1
52.12	2.57	13.89	3.79	4.65	0.25	6.56	6.40	3.40	4.94	0.71	0.92	...	0.16	100.34	2
53.36	2.57	13.15	1.67	6.37	0.17	6.13	5.47	3.55	5.76	0.68	0.92	...	0.08	100.35	3
47.15	2.46	14.27	9.32	1.44	0.18	7.78	8.32	3.25	4.56	1.07	0.79	...	...	100.59	4
47.96	2.83	13.24	2.93	7.87	0.02	7.48	8.02	3.79	4.89	1.03	0.42	...	...	100.48	5
48.70	2.58	17.84	3.98	3.87	0.12	5.56	6.04	3.45	5.31	1.21	1.71	...	...	100.37	6
50.54	2.05	14.50	2.31	6.96	0.55	7.41	7.01	3.57	4.28	1.05	0.69	...	...	100.33	7
50.81	2.19	14.71	2.36	6.20	0.14	7.43	6.65	3.56	5.61	1.06	0.29	...	...	100.61	8
52.68	1.88	14.38	1.43	7.76	0.15	6.38	5.82	3.36	5.43	1.10	0.11	...	...	100.48	9
52.94	2.00	14.69	0.89	8.05	0.15	6.08	6.01	3.35	5.13	1.01	0.32	...	...	100.62	10
53.46	2.77	14.61	1.78	3.89	0.01	6.16	5.92	3.33	5.20	0.92	0.37	...	...	100.47	11
50.58	2.56	14.14	4.48	4.61	0.10	6.68	5.08	4.08	4.01	1.04	1.26	...	...	100.08	12
51.12	2.45	13.76	1.28	6.70	0.12	6.95	6.44	4.22	5.61	1.06	2.61	...	...	100.20	13
51.26	2.42	14.66	7.84	1.30	0.08	4.21	6.27	4.54	5.27	1.14	1.19	...	...	100.18	14
42.72	2.40	14.62	3.62	7.88	0.25	8.95	9.18	3.70	2.84	0.76	3.01	...	0.12	100.27	15
42.80	2.22	14.01	4.79	7.84	0.22	5.79	8.94	3.80	3.57	1.43	4.72	...	...	100.13	16
46.56	2.02	16.59	2.85	7.61	0.21	6.68	8.02	3.42	3.24	0.59	0.52	...	...	100.29	17
46.68	2.88	15.74	6.23	6.58	0.26	4.47	8.76	3.36	2.26	0.90	2.13	...	...	100.25	18
48.76	2.01	16.13	2.96	7.29	0.24	6.77	8.02	3.06	2.32	0.68	1.89	...	...	100.13	19
49.04	1.40	18.02	4.26	6.12	0.20	4.98	6.88	4.74	3.30	0.60	0.73	...	...	100.27	20
47.52	4.16	15.67	7.81	4.47	0.21	3.78	8.18	4.17	2.22	0.76	0.68	0.30	...	99.98	21
46.74	1.82	14.64	4.63	9.48	0.22	8.15	8.01	3.69	2.31	0.50	0.49	...	...	100.68	22
44.98	2.89	15.56	5.15	7.30	0.23	3.31	9.20	5.34	1.29	0.43	3.77	...	...	99.46	23
42.23	2.00	12.46	2.89	10.93	...	11.81	10.31	3.91	1.73	0.50	1.30	...	...	100.60	24
45.51	2.05	14.96	2.22	9.95	...	8.78	9.16	3.50	1.78	0.58	1.30	...	...	100.00	25
45.42	2.42	13.10	4.51	7.66	0.23	9.30	10.62	2.82	1.57	0.50	1.19	...	...	100.30	26
46.12	3.04	16.38	3.72	6.63	0.18	3.26	10.16	4.67	3.07	0.81	1.35	0.56	0.30	100.25	27
47.88	2.52	15.09	3.59	8.59	0.19	4.96	8.82	3.31	1.59	0.58	2.92	...	0.27	100.31	28
48.16	2.00	14.74	2.75	7.45	0.16	6.55	10.06	3.28	2.09	0.14	2.42	...	...	100.07	29
42.98	3.18	13.67	4.13	9.45	0.21	7.89	10.06	4.27	2.11	0.87	0.68	...	0.64	100.35	30
47.06	2.22	13.81	3.27	8.64	0.17	9.21	9.82	3.27	1.34	0.49	0.94	...	0.11	100.35	31
42.40	2.13	14.50	3.58	8.57	0.24	6.17	9.42	4.90	2.36	1.31	4.54	...	...	100.19	32
42.56	2.28	14.55	4.70	8.57	0.25	7.54	8.72	4.31	1.72	1.03	3.90	...	...	100.13	33
46.24	2.02	16.19	4.46	6.66	0.12	7.27	9.08	3.36	1.66	0.51	1.88	...	...	99.76	34
47.64	2.02	15.17	8.57	2.85	0.18	7.63	10.08	3.28	1.34	0.65	0.72	...	...	100.40	35
46.54	3.46	14.41	7.07	4.49	0.15	4.88	8.81	5.07	1.18	1.88	0.96	1.18	0.27	100.08	36
41.13	2.62	12.00	4.27	9.94	0.17	9.42	10.97	5.22	2.24	1.32	0.68	0.27	...	100.25	37
42.64	3.44	12.32	5.56	7.85	0.06	9.14	11.38	3.58	1.39	0.57	2.53	...	...	100.46	38
44.25	1.61	15.23	7.71	3.42	0.09	4.53	4.02	1.27	0.75	0.82	3.96	8.23	0.09	99.98	39
44.82	1.70	17.59	6.32	5.21	...	5.78	8.51	2.16	1.21	0.73	2.83	3.56	0.15	100.57	40
47.17	3.12	15.16	4.03	6.88	0.22	7.39	8.41	3.21	1.07	0.69	1.28	1.57	0.39	100.48	41
47.70	1.95	16.28	5.26	5.96	0.09	5.31	8.41	2.81	1.53	1.13	0.45	1.83	0.29	99.13	42
48.26	3.57	15.27	6.51	4.49	0.12	6.21	8.34	4.32	1.14	0.07	0.86	0.47	0.29	100.55	43
49.95	2.58	16.30	8.87	2.72	0.13	4.12	9.14	3.89	1.55	0.58	0.19	0.87	0.21	100.10	44
50.10	1.53	17.78	6.38	4.09	0.10	4.47	8.07	3.86	1.76	0.46	0.35	1.25	0.13	100.31	45
50.89	1.53	18.33	7.78	2.57	...	3.65	7.38	3.86	1.91	0.43	0.94	1.23	0.12	100.62	46

# INTERNATIONAL GEOLOGY REVIEW

TABLE 1. The chemical composition of the Cenozoic basaltic rocks of eastern China

No.	Rock type <sup>1</sup>	Locality	Reference
47	Olivine basalt	Fang-shan of Chiang-ning, Kiangsu	Yeh Liang-fu et al[18]
48	Olivine basalt	Ch'ih-shan of Chu-jung, Kiangsu	Shen Yung-ho [29]
49	Coarse-grained basalt		
51	Olivine basalt	Chu-t'ou-shan of P'u-chen, Kiangsu	Shen Yung-ho [30]
52	Olivine basalt	Mao-shan of Chü-jung, Kiangsu	Yeh Liang-fu et al.[18]
53	Olivine basalt	She-wu-shan of Chiang-ning, Kiangsu	Shen Yung-ho et al[31]
54	Pyroxene basalt		
55	Pyroxene basalt	Yung-hsing, Hainan Island	T. Ichimura [24]
56	Olivine basalt	Pai-lien, Hainan Island	
57	Olivine pyroxene basalt	T'an-kou, Hainan Island	
58	Trachybasalt	Wei-chou-tao, Kwangsi	K. Yagi [37]
61	Alkali basalt	Ts'ao-ling of Hsin-chu, Taiwan	Yen-Tsang-po [27]
62	Analcite basanite	Ma-wu-tu of Hsin-chu, Taiwan	T. Ichimura [23]
63	Olivine basalt		
64	Pyroxene-olivine basalt	Kuan-yin-shan of Tan-shui, Taiwan	T. Ichimura [29]
65			
66			
67			
68			
69	Two pyroxene andesite		
70	Augite andesite with abundant glass	Pai-t'ou-shan of Ch'ang-pai, Kirin	A. Lacroix [14]
71	Hypersthene-hornblende andesite		
72	Hypersthene andesite		
73	Hypersthene-hornblende andesite		
74	Trachytic obsidian		
75	Sodic pyroxene		
76	Glassy trachyte		
77	Glassy alkalic lava rock		S. Kozu [33]
78	Sub-alkalic rhyolite		A. Lacroix [14]
79	Sub-alkalic rhyolite		Nemoto [38]
80	Alkali-rhyolite		A. Lacroix [14]

<sup>1</sup>Based on rock types given in the original article. Number 25 is the average of 7 basalts. The Ch'ao-yang; the coarse basalt of Lien-shan of Chin-hsi (Lacroix) and the basalts of Abtzikh -

40 percent of the rocks contain more than 50 percent SiO<sub>2</sub>, the highest being 55.51 percent. Their alumina content is also high. About 50 percent of the rocks contain more than 10 percent Al<sub>2</sub>O<sub>3</sub>, the highest being 18.97 percent. About 50 percent of the rocks contain more than 5 percent MgO. The Na<sub>2</sub>O and K<sub>2</sub>O contents are also rather high. About 25 percent of the rocks contain more than 4 percent of Na<sub>2</sub>O and about 50 percent of the rocks contain

more than 1.5 percent of K<sub>2</sub>O. The basalt just north of the Yangtze River (no. 53) contains 4.67 percent Na<sub>2</sub>O. Basalt of Mao-shan of Chü-jung (no. 54) contains as much as 2.11 percent of K<sub>2</sub>O, and so resembles those of northern China. Mineralogically the early extrusives are largely olivine basalts and the later extrusives are basalts containing phenocrysts of sodic feldspar [26, 30, 31, 32]. Hypersthene basalt and quartz basalt have been noted on Hainan Island.



# CHAO TSUNG-PU

including some andesites, trachytes and alkalic rocks (Concluded)

SiO <sub>2</sub>	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	P <sub>2</sub> O <sub>5</sub>	H <sub>2</sub> O (+)	H <sub>2</sub> O (-)	Other	Total	No.
51.86	2.25	14.80	7.83	2.72	...	4.11	8.06	3.81	1.97	0.51	1.10	1.30	...	100.12	47
46.28	3.47	11.84	9.04	4.44	0.05	6.58	8.97	4.47	1.21	0.43	1.76	1.92	...	100.37	48
49.75	1.19	16.25	5.95	4.81	0.07	5.55	8.55	3.83	1.45	0.23	1.45	1.49	...	100.71	49
51.04	1.22	17.12	6.10	3.82	0.08	4.72	8.13	4.56	1.66	0.26	1.05	1.20	...	100.96	50
48.59	1.95	8.67	9.93	6.41	0.01	7.56	8.59	3.45	1.19	0.22	2.68	1.67	...	100.90	51
48.92	1.45	18.19	8.03	3.33	0.07	2.59	6.41	4.49	1.70	0.33	1.49	3.96	...	100.76	52
51.86	2.35	8.83	10.97	5.30	0.04	4.57	8.90	4.67	1.59	0.28	0.67	0.83	...	100.86	53
48.04	2.13	14.99	6.02	4.89	0.52	7.07	8.58	3.66	2.11	...	0.50	1.10	...	99.61	54
51.26	2.13	14.48	4.47	6.39	...	5.52	9.28	3.16	1.21	0.44	0.90	1.20	...	100.70	55
51.80	1.31	15.71	4.44	6.66	0.01	5.18	8.60	3.47	0.50	0.25	1.15	1.32	...	100.04	56
43.95	1.57	17.23	4.71	7.91	0.19	8.71	11.19	2.18	1.18	0.85	0.39	1.57	...	100.60	57
52.17	1.58	18.97	3.05	8.74	0.14	1.68	7.85	3.66	1.33	0.07	0.57	0.79	...	100.60	58
55.51	1.48	17.27	1.44	9.70	0.15	3.40	8.89	2.99	1.99	0.27	0.32	0.06	...	100.47	59
48.98	2.88	14.12	2.25	7.40	0.15	7.98	10.30	2.61	1.61	0.30	1.02	0.32	...	99.93	60
48.32	0.34	12.68	2.95	4.92	0.18	15.42	7.45	3.60	3.46	...	0.58	...	...	99.90	61
46.82	0.35	12.64	3.67	4.71	0.18	15.42	7.06	1.64	4.00	...	2.72	...	...	99.66	62
42.94	3.11	13.90	1.32	8.12	tr.	12.79	9.27	2.97	1.56	1.05	3.16	...	...	100.71	63
41.92	0.81	12.70	6.39	8.13	0.21	12.01	9.97	3.90	0.48	...	3.11	...	...	99.63	64
47.42	0.72	13.88	3.83	8.26	0.18	8.76	9.13	3.55	1.44	...	2.60	...	...	99.57	65
49.42	0.61	21.54	2.56	5.60	0.14	5.48	9.30	2.43	1.63	...	1.62	...	...	100.33	66
50.03	0.96	18.00	2.22	6.73	0.60	7.83	9.82	2.43	1.69	...	0.60	...	...	100.37	67
50.97	1.08	16.75	2.23	6.29	0.07	8.57	9.70	2.46	1.78	...	0.50	...	...	100.40	68
54.88	0.44	21.90	1.92	2.73	0.14	4.56	6.22	3.10	1.99	...	1.72	...	...	99.60	69
55.42	0.42	21.18	1.60	3.59	0.11	4.89	6.61	3.38	2.02	...	1.16	...	...	100.38	70
57.15	0.49	20.57	2.25	2.34	0.06	3.01	6.64	4.39	1.59	...	1.37	...	...	99.86	71
60.33	0.43	20.07	1.92	2.49	0.03	3.22	5.14	3.69	1.77	...	1.29	...	...	100.38	72
62.32	0.31	20.14	1.92	1.85	0.88	2.68	4.42	4.01	1.62	...	0.74	...	...	100.90	73
65.84	0.66	15.39	1.45	3.55	0.17	0.03	1.50	5.96	5.27	0.12	0.21	0.08	...	100.23	74
67.42	0.72	15.07	0.44	2.79	0.14	0.25	1.42	6.11	5.01	0.07	0.36	0.05	...	99.85	75
67.68	0.31	12.55	3.00	2.85	0.06	0.24	1.25	6.31	4.71	0.19	0.51	0.08	...	99.74	76
20.81	0.11	10.63	2.60	4.01	0.10	0.23	0.75	5.97	3.47	0.05	0.93	0.40	...	100.16	77
77.76	0.38	11.65	2.51	3.23	0.10	...	0.62	4.68	4.51	0.05	0.59	0.22	...	100.30	78
72.76	0.29	11.06	2.94	2.46	0.05	0.10	0.59	4.55	4.33	0.08	0.71	0.33	...	100.25	79
73.20	0.60	9.31	3.25	3.10	0.19	0.04	0.38	5.25	4.43	0.10	0.28	0.12	...	100.25	80

basalts of Ti-shui-yen, Hsua-hua (Wang Heng-sheng); the coarse basalts of Ta-t'ing-fang of kairkhan Mountain (P. Venukoff) etc., were not included because their age is unknown.

## Northern China and southern Manchuria

The basalts of this region are lower in silica. About 30 percent of these basalts contain less than 45 percent SiO<sub>2</sub>; the lowest being 41.13 percent. They also are low in alumina. About 60 percent of the samples have less than 15 percent Al<sub>2</sub>O<sub>3</sub>. The Na<sub>2</sub>O and K<sub>2</sub>O contents are higher. About 30 percent of the samples have total alkalis in excess of 6 percent. In

some areas Na<sub>2</sub>O exceeds 5 percent. Generally the Na<sub>2</sub>O content is greater than that of K<sub>2</sub>O. The basalts of the Mu-leng region of eastern Heilungkiang are high in K<sub>2</sub>O, and some that contain as much as 3.57 percent resemble those of northern Manchuria. Mineralogically they are characterized by the presence of titanite and richness of olivine. The plagioclase is mostly of intermediate composition and the groundmass contains potassium andesine, anorthoclase and brownish alkalic.

glass. The trachybasalt of Ch'i-hsin-shan of Shuang-liao contains leucite, aegirine and rhönite, etc. Nepheline basalts are also found in Shantung and Liaoning.

#### Northern Manchuria

The region includes the northern part of Heilungkiang and the northeastern part of Inner Mongolia. The basalts are higher in silica. About 70 percent of the samples contain more than 50 percent  $\text{SiO}_2$ , the highest being 53.46 percent. They are characterized chemically by  $\text{K}_2\text{O}$  in excess of  $\text{Na}_2\text{O}$ ; about 80 percent of the samples have  $\text{Na}_2\text{O} + \text{K}_2\text{O}$  greater than 8 percent; and 60 percent of the samples have  $\text{K}_2\text{O}$  greater than 5 percent, the highest being 5.76 percent. Mineralogically besides olivine, pyroxene and glass, the rock contains anorthoclase, leucite, biotite and extraneous quartz.

#### Taiwan

Although the distribution of basalts in Taiwan is of limited extent, they cover a wide range chemically. For example, the basalt from Kuang yin-shan of Tan-shui contains about 50 percent  $\text{SiO}_2$ , a high content of alumina (21.54 percent) and  $\text{Na}_2\text{O} + \text{K}_2\text{O}$  about 4 percent. The basalt from the Hsin-chu region however contains 41.92 percent  $\text{SiO}_2$  with  $\text{MgO}$  15.42 percent and  $\text{Na}_2\text{O} + \text{K}_2\text{O}$  about 7.0 percent. The former are pyroxene-olivine basalt differentiating into two-pyroxene andesite and hornblende andesite. The latter are basalts containing analcite, leucite, orthoclase, and biotite, etc.

#### The Normative Mineral Composition and Niggli Values

By averaging the analyses of basaltic rocks from adjacent areas listed in Table 1, the representative chemical composition of a particular area can be obtained. Furthermore, the norm, the Niggli and Zavaritsky values of basalts of various regions can be calculated. These values are given in Tables 2A and 2B. Table 2A lists 21 areas shown in Figure 1. Figures 2 and 3 are plots of the normative mineral composition given in Tables 2A and 2B. Figures 4 to 7 are plots of the Niggli values and Figure 8 is the plot showing the Zavaritsky values. For comparison and reference, the average composition of the various types of basalts of the world is given in Table 3A, those of the alkali basalts of New Zealand and Uganda are given in Table 4A and the average composition of the basalts of various areas in the world in Table 7A. The calculated Niggli values and Zavaritsky value of the data in 3A, 4A, and 7A are given in Tables 3B, 4B, and 7B.

#### The Normative Feldspar Composition

From Table 2A, the normative or of the

basalts of the southern China region is less than 10 percent whereas the or value of the northern China and southern Manchuria region is higher than 10 percent. The or value of basalts of the Mu-leng area is increased to 17.23 percent and the ab value is high for no. 14 (P'u-chen), no. 12 (Ching-ching) and no. 16 (Chü-jung) ranging from 34 percent to 37 percent. The an value is lowest for rocks of northern Manchuria, less than 10 percent, and highest for no. 21 (Kuan-yin-shan) of Taiwan which is 35.3 percent. This is clearly evident from the triangular diagram which shows the normative feldspar composition in weight percent (see fig. 2). As compared with the various types of basalts of the world, only no. 15 (Fang-shan near Nanking), no. 18 (Hainan Island) and no. 21 (Kuan-yin-shan of Taiwan) etc., are similar to them in normative feldspar composition. Basalts of other areas except those of northern Manchuria fall within the range of normative composition of alkali basalts of Eastern Otago, New Zealand (a, b, c, d). The basalts of northern Manchuria contain even higher or content than the leucite basanite of Uganda, Africa. The diagram further shows that the normative feldspar compositions of basalts of the various areas of China are concentrated in various parts of the diagram, for example the normative composition of basalts of northern Manchuria (W) and northern China and southern Manchuria (N) contain nepheline (nos. 1-13, table 2A), indicating that they are also undersaturated with respect to silica. The composition of basalts of southern China (F) contains normative quartz (nos. 14-18, table 2A) indicating that they are saturated with respect to silica. The basalt of Kuan-yin-shan of Taiwan, (no. 21) although undersaturated, does not contain normative nepheline. The basalts of eastern China, except those of Kuan-yin-shan of Taiwan and Hainan Island, are generally rich in normative or and ab. Nevertheless, the basalts of Kuan-yin-shan of Taiwan and Hainan Island, are higher in normative or than the average calc-alkalic basalts of other parts of the world (I, II, III, IV). Their normative composition is similar to those average alkali basalts of New Zealand (a, b, c, d) and the feldspathoid-bearing basalts (V, VI, VII) of the world.

#### The Normative Pyroxene Composition

Figure 3 shows, in weight percent, the normative pyroxene composition. The triangular diagram shows that, except those of southern China and Taiwan, the normative pyroxene composition of the basalts is concentrated near the Di-Hd line, rich in wo. The basalts of southern China are rich in normative en; the plots are scattered within the En-Di-Hi-Fs area. As compared to the average composition of basalts of the world, the pyroxenes of basalts of Hainan Island and of Kuan-yin-shan of Taiwan (no. 18 and 21) are poor in the wo molecule which resembles those of the tholeiitic basalt (I, II).



TABLE 2A. The chemical composition of the Cenozoic basalts of eastern China (regional average)

Region composition	1	2	3	W	4	5	6	7	8	9	10	11	12	13	N	14	15	16	17	18	19	F	20	21(k)	C
SiO <sub>2</sub>	49.44	50.53	51.02	50.39	46.10	47.52	46.74	44.98	45.10	45.02	46.90	44.71	46.54	41.88	45.45	49.80	48.43	48.70	50.48	50.56	48.47	49.20	45.48	50.14	47.56
TiO <sub>2</sub>	2.81	2.34	2.47	2.40	2.93	4.16	1.82	2.89	2.04	2.70	2.50	2.11	3.46	3.03	2.38	1.92	2.20	1.96	1.86	1.54	2.88	2.02	1.07	1.70	2.19
Al <sub>2</sub> O <sub>3</sub>	13.22	14.78	14.08	14.32	15.87	15.67	14.64	15.56	14.65	13.74	14.83	15.10	14.41	12.16	14.80	11.89	16.30	15.07	15.06	17.49	14.12	15.45	13.16	18.76	14.94
Fe <sub>2</sub> O <sub>3</sub>	3.77	3.12	3.72	3.49	4.12	7.81	4.63	5.15	2.30	3.70	3.64	5.33	7.07	4.91	4.43	9.64	6.74	7.03	4.98	3.07	2.25	6.23	3.63	2.34	4.75
FeO	5.15	6.00	4.80	5.43	7.22	4.47	9.48	7.30	10.07	9.04	7.58	6.66	4.48	8.89	8.08	5.01	4.23	4.39	5.98	8.78	7.40	5.95	6.83	6.20	6.82
MnO	0.20	0.11	0.11	0.13	0.23	0.21	0.22	0.23	0.18	0.19	0.19	0.20	0.15	0.12	0.06	0.04	0.07	0.06	...	0.16	0.15	0.07	0.15	0.09	0.14
MgO	8.17	6.78	6.19	6.90	6.27	3.28	8.15	3.11	19.16	8.55	6.02	7.15	4.88	8.28	7.31	4.91	5.06	5.61	5.92	4.56	7.98	5.30	12.82	7.29	7.00
CaO	7.44	6.72	6.22	6.74	8.30	8.18	8.01	9.20	9.30	9.94	9.91	9.32	8.81	11.18	9.25	7.97	8.27	8.58	8.82	9.31	10.30	8.58	8.57	9.60	8.50
Na <sub>2</sub> O	3.11	3.46	4.27	3.48	3.76	4.17	3.69	5.34	3.55	3.77	3.52	3.96	5.07	4.40	3.83	4.20	3.24	4.28	4.43	2.94	2.61	3.47	3.13	2.44	3.60
K <sub>2</sub> O	4.79	5.05	5.33	5.03	2.92	2.22	2.31	1.29	1.77	1.72	2.08	1.77	1.18	1.81	2.01	1.49	1.43	1.41	1.27	1.49	1.61	1.43	2.19	1.70	2.44
P <sub>2</sub> O <sub>5</sub>	0.65	1.06	1.07	0.97	0.83	0.76	0.50	0.43	0.58	0.66	0.58	0.87	1.88	0.95	0.74	0.28	0.67	0.32	0.40	0.88	0.30	0.46	2.43	...	0.67
H <sub>2</sub> O	1.78	0.59	0.85	0.92	2.50	0.98	0.49	3.77	1.30	0.81	2.95	2.76	2.14	1.74	1.91	3.90	3.59	2.96	1.83	...	1.35	3.40	...	0.87	1.82
Q	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Or	28.31	29.47	31.13	30.02	17.23	12.79	13.34	7.78	...	...	...	...	7.23	10.56	...	1.96	3.06	0.48	0.78	0.12	...	1.26	...	...	...
Ab	14.67	18.96	19.91	17.82	17.81	32.75	18.34	22.08	12.58	13.88	20.43	19.38	36.68	2.62	17.29	35.63	27.25	34.06	7.78	8.89	9.45	8.34	12.79	10.00	14.46
An	7.78	10.01	3.61	8.34	17.79	17.51	16.40	14.45	18.90	15.29	18.62	18.07	12.79	8.34	17.24	9.17	25.85	17.79	21.96	30.30	21.56	22.24	15.56	35.30	17.24
Ne	5.96	5.68	8.80	6.25	10.22	2.12	6.81	12.49	9.37	11.64	4.83	7.66	3.41	18.74	8.24	...	...	...	...	...	...	...	8.52	...	2.69
Wo	10.55	7.31	8.58	8.35	7.65	7.89	8.58	11.95	9.68	12.41	11.37	9.62	13.60	17.28	10.21	10.8	4.52	9.63	8.00	5.22	11.48	7.07	11.25	5.10	8.70
En	8.40	5.20	6.80	6.30	5.00	6.80	5.30	6.60	5.90	8.00	7.30	6.80	11.80	10.90	6.80	12.1	12.60	8.30	14.60	11.30	12.20	13.20	8.10	11.00	6.30
Fs	0.92	1.45	0.79	1.19	2.11	...	2.77	4.88	3.66	3.56	3.30	1.98	...	5.28	2.64	...	...	...	5.41	9.35	4.34	2.51	2.11	4.88	1.58
Fe	8.26	8.19	6.02	7.63	7.35	1.42	10.43	1.54	12.26	9.24	5.32	7.63	0.21	6.72	8.05	...	...	...	...	...	5.46	...	15.54	5.04	7.77
Fa	1.55	0.82	1.63	3.47	...	...	6.32	1.02	7.55	4.59	2.65	2.14	...	3.67	3.67	...	...	...	...	...	2.24	...	4.49	2.45	2.35
Mt	2.35	2.48	2.02	2.01	2.02	1.01	1.01	1.01	1.30	1.01	1.30	2.02	4.37	2.33	1.65	0.65	1.68	0.67	1.01	1.01	0.67	1.34	...	...	1.68
Ap	5.57	4.41	5.33	5.10	6.03	3.02	6.72	4.22	3.25	5.33	5.34	7.65	4.87	5.47	5.96	10.67	7.19	8.81	7.19	4.40	3.25	9.05	5.33	3.25	6.73
Il	5.32	4.41	4.71	4.41	3.66	8.06	3.50	5.47	3.81	5.16	5.17	3.95	6.53	6.96	4.41	3.65	4.25	3.65	1.67	2.89	5.47	3.80	2.13	1.67	3.26
Hm	...	...	...	...	...	...	...	...	...	...	...	...	3.68	...	...	2.32	1.76	0.96	...	...	...	...	...	...	...
Or	55.7	50.5	57.0	53.4	32.6	20.6	27.7	17.5	25.1	25.5	23.8	22.0	12.8	49.0	25.2	16.6	13.5	13.8	13.3	13.9	17.8	13.9	33.0	15.2	20.2
Wt% <sub>Ab</sub>	28.9	32.3	36.5	31.7	33.7	51.1	38.1	50.0	29.9	35.4	39.8	40.4	64.6	12.1	37.4	66.4	44.3	55.0	47.5	38.6	41.2	49.0	27.0	30.0	42.6
Wt% <sub>An</sub>	15.4	17.2	6.5	14.9	33.8	28.2	34.2	32.5	45.0	39.1	36.4	37.6	22.6	38.9	57.4	17.0	42.2	31.2	37.2	47.5	41.0	37.1	40.0	54.8	31.2
Wt% <sub>Wo</sub>	53.0	52.4	53.0	52.8	51.9	53.8	51.6	51.0	53.3	51.7	51.8	52.2	53.6	51.6	52.0	50.3	26.4	53.7	28.6	20.1	40.9	31.0	52.4	24.3	52.5
Wt% <sub>En</sub>	42.2	37.2	42.0	39.7	33.8	46.2	31.8	28.2	30.3	33.4	33.2	36.8	46.4	32.6	34.6	49.7	73.6	46.3	52.1	43.8	43.5	58.0	37.7	52.5	38.0
Wt% <sub>Fs</sub>	4.8	10.4	5.0	7.5	14.3	...	16.6	20.8	16.4	17.1	15.0	11.0	...	15.8	13.4	...	...	...	19.3	36.1	15.6	11.0	9.9	23.2	9.5

Note applying to Tables 2A and 2B: Regions; 1) Vicinity of Nen-chiang, Heilungkiang (av. of 3, A.N. Zavaritsky, 1936. 2) Wu-ta-lien-ch'ih of Te-tu, Heilungkiang (av. of 9, Ogura, T. 1936, 1941). 3) Erh-k'e-shan of K'e-tung, Heilungkiang (av. of 3, Ogura, T. and others, 1938, 1941). 4) Mu-leng area, Heilungkiang (av. of 6, A. Lacroix, 1929). 5) Pai-t'ou-shan of Ch'ang-pai, Kirin (1 analysis, A. Lacroix, 1928). 6) Lung-wan of Ching-yü, Kirin (1 analysis, Ogura, T. 1941). 7) Ying-o-men of Ch'ing-yuan, Liaoning (1 analysis, Koto, 1912). 8) Ch'i-hsin-shan of Shuang-liao, Liaoning (av. of 8, Ogura, 1941). 9) Northwest of Ta-er-po, Inner Mongolia (av. of 2, A. Lacroix, 1928). 10) Wei-ch'ang area, Hopei (av. of 4, Lacroix, 1928) (continued at bottom of Table 2B, p. 206)

TABLE 2B. Niggli and Zavaritsky values of the Cenozoic basalts of eastern China

Region	1	2	3	W	4	5	6	7	8	9	10	11	12	13	N	14	15	16	17	18	19	F	20	21(k)	C
Niggli value	Si	118.1	126.8	132.2	130.0	108.8	122.2	104.0	112.3	96.0	111.1	101.0	116.5	87.7	101.6	128.7	125.0	125.1	128.5	124.5	114.0	122.6	93.6	118.0	111.8
	Al	18.7	21.8	21.5	21.1	22.0	23.8	18.9	22.8	18.5	17.3	20.6	20.1	21.2	15.0	19.5	17.9	24.9	22.0	25.4	19.5	22.6	16.0	26.0	20.6
	fm	47.1	43.8	41.7	44.1	43.9	39.4	51.0	37.6	50.0	49.7	43.1	46.0	40.9	49.3	47.2	47.5	41.8	43.0	43.8	40.6	46.5	43.9	18.0	41.8
	c	19.5	18.1	17.3	18.0	20.9	22.5	18.9	24.6	21.4	22.8	25.2	22.5	23.6	24.9	22.2	21.7	22.9	23.0	23.6	24.5	26.0	22.9	19.0	24.2
	Alk	14.7	16.3	19.5	16.3	13.2	14.1	11.0	15.0	9.7	10.2	11.1	11.4	14.3	11.8	11.1	12.9	10.4	11.2	10.4	9.5	8.0	10.6	9.0	8.0
	mg	0.62	0.58	0.60	0.59	0.56	0.36	0.52	0.33	0.57	0.55	0.49	0.52	0.44	0.53	0.52	0.39	0.47	0.48	0.54	0.41	0.60	0.45	0.68	0.61
	K	0.50	0.45	0.44	0.49	0.31	0.25	0.28	0.14	0.25	0.23	0.28	0.23	0.14	0.21	0.25	0.19	0.22	0.18	0.20	0.25	0.29	0.21	0.32	0.31
	al-alk	4.0	5.5	2.0	4.3	6.8	9.7	7.8	7.8	8.8	7.1	9.5	8.7	6.9	3.2	8.4	5.0	14.5	10.8	11.8	15.9	11.5	12.0	7.0	18.0
	alk	3.7	3.0	9.7	5.0	1.9	1.4	1.4	1.9	1.1	1.4	1.2	1.3	2.0	3.7	1.3	2.6	0.7	1.0	0.9	0.6	0.7	0.9	1.3	0.4
	C-(al-alk)	15.5	12.6	15.3	13.7	14.1	12.8	11.1	16.8	12.6	15.7	15.7	13.8	16.7	21.7	13.8	16.7	8.4	12.2	11.8	8.6	14.5	10.9	12.0	6.2
Zavaritsky value	qz	-10.7	-38.4	-45.8	-37.2	-33.0	-34.2	-40.4	-47.9	-42.8	-41.0	-33.3	-45.6	-40.7	-59.5	-42.8	-24.0	-16.6	-19.7	-14.9	-18.0	-19.8	-42.4	-14.0	-35.8
	ti	5.0	4.4	4.8	4.4	3.8	8.0	3.0	5.4	3.2	4.4	4.8	4.4	6.4	4.7	3.9	3.6	4.3	3.5	1.5	2.8	5.1	3.7	1.7	1.5
	p	0.7	1.0	1.2	0.9	0.8	0.8	0.4	0.4	0.5	0.6	0.6	0.8	2.0	0.9	0.7	0.3	0.8	0.3	0.4	0.4	0.3	0.4	...	0.6
	a	13.3	14.5	16.5	14.6	12.7	12.7	11.2	14.3	10.2	10.5	10.7	11.5	11.9	12.0	11.3	11.4	9.0	11.6	9.6	8.8	7.9	9.9	9.5	8.0
	c	1.2	2.4	0.8	2.0	4.5	4.4	4.0	3.7	4.5	3.7	4.6	4.5	4.0	2.0	4.2	2.2	6.3	4.4	5.5	7.6	5.3	5.5	3.6	8.8
	b	28.4	25.1	24.2	25.5	28.0	23.8	31.3	26.0	32.0	33.8	28.5	30.5	24.1	37.1	30.9	28.5	21.8	26.2	26.7	23.2	29.4	26.0	36.2	23.8
	s	57.1	58.0	58.5	57.9	54.8	59.1	53.5	56.0	53.3	52.0	56.2	53.5	60.0	48.9	53.6	57.9	62.9	57.8	58.2	60.4	58.6	50.7	59.4	54.5
	f'	28.9	29.9	31.2	31.5	39.5	47.7	43.1	46.8	34.3	34.4	37.4	36.8	41.5	33.2	36.7	45.4	44.3	40.1	39.3	48.8	30.6	42.8	27.6	33.8
	m'	46.6	45.0	42.0	45.0	39.4	27.6	43.0	22.6	45.7	41.6	36.0	40.2	32.8	36.6	40.7	28.6	39.0	36.4	39.6	34.0	45.4	35.2	54.9	53.2
	c'	24.5	25.1	26.8	23.5	21.1	24.7	18.9	30.6	20.0	24.0	26.6	23.0	25.7	30.2	22.6	26.0	16.7	23.5	21.1	17.2	24.0	22.0	17.5	13.0
	n	50.0	51.3	55.2	51.0	66.0	74.7	71.3	84.0	75.0	76.0	72.0	77.0	86.3	79.0	74.7	81.0	77.6	82.1	90.0	75.0	71.2	78.8	68.5	69.0

11) Hanorpa of Wan-ch'uan, Hopei (av. of 4, A. Lacroix, 1928). 12) Hsueh-hua-shan of Ching-ching, Hopei (1 analysis, Tomita, 1933). 13) Ch'i-hsia and T'ai-shan of Shantung (av. of 2, Harumoto, 1949 and A. Lacroix, 1928). 14) Chu-t'ou-shan of P'u-chen, Kiangsu (av. of 3, Shen Yung-ho, 1951). 15) Fang-shan of Chiang-ning, Kiangsu (av. of 9, Chen Yü-chi and Shen Yung-ho, 1948; Yeh, L. F., and Yü, T. Y., 1934). 16) Ch'ih-shan of Chü-jung, Kiangsu (av. of 3, Shen Yung-ho, 1951). 17) Mao-shan and She-wu-shan, Chü-jung, Kiangsu (av. of 3, Yeh, L. F. and Yü, T. Y., 1934) Yagi, 1949). 20) Hsin-chu area, Taiwan (av. of 5, Ichimura, 1943; Yeh, T. P., 1949). 21) Kuan-yin-shan of Tan-hsui, Taiwan (av. of 3, Ichimura, 1950). W. northern Manchuria region (av. of 14, new average). N. northern China and southern Manchuria (av. of 30, new average). C. eastern China (av. of 71, not including those from Kiangsu).



# CHAO TSUNG-PU

TABLE 3A. Average chemical composition of the basalts of the world

Rock type Composition	I	II	III	IV	V	VI	VII	
SiO <sub>2</sub>	50.83	47.90	45.73	43.69	47.34	44.82	45.75	
Al <sub>2</sub> O <sub>3</sub>	14.07	11.84	14.64	9.06	16.59	15.42	17.07	
Fe <sub>2</sub> O <sub>3</sub>	2.88	2.32	3.16	3.46	4.50	4.28	5.44	
FeO	9.06	9.80	8.73	9.43	5.72	6.61	3.82	
MnO	0.18	0.15	0.20	0.16	0.20	0.16	0.14	
MgO	6.34	14.07	9.39	19.68	5.04	7.27	6.36	
CaO	10.42	9.29	10.74	9.18	8.65	10.32	9.67	
Na <sub>2</sub> O	2.23	1.66	2.63	1.49	5.33	5.30	4.99	
K <sub>2</sub> O	0.82	0.54	0.95	0.69	2.63	1.26	1.25	
H <sub>2</sub> O	0.91	0.59	0.76	0.74	0.87	1.56	2.48	
TiO <sub>2</sub>	2.03	1.65	2.63	2.12	2.53	2.65	2.36	
P <sub>2</sub> O <sub>5</sub>	0.23	0.19	0.39	0.30	0.60	0.35	0.67	
Q	3.5	...	...	...	...	...	...	
Or	5.0	2.8	6.1	3.9	15.6	7.8	7.8	
Ab	18.9	14.1	18.3	11.0	18.3	12.6	22.0	
An	25.9	23.4	24.7	16.1	13.6	14.5	20.3	
Ne	...	...	2.3	0.9	14.5	17.3	10.9	
Wo	10.3	9.1	10.8	11.5	10.7	14.3	9.5	
En	15.8	20.5	7.1	8.4	7.8	10.4	8.2	
Fs	11.2	7.9	2.9	2.0	1.8	2.5	...	
Fo	...	10.3	11.5	28.6	3.4	5.5	5.4	
Fa	...	4.4	5.0	7.1	0.8	1.5	...	
Mt	4.2	3.3	4.6	5.1	6.5	6.3	5.8	
Il	3.8	3.2	5.0	4.0	4.9	5.0	4.6	
Ap	0.5	0.4	1.0	0.6	1.4	0.8	1.6	
Wt% {	Or	10	7	12	13	33	22	15
	Ab	38	35	37	35	38	36	44
	An	52	58	51	52	29	42	41
Wt% {	Wo	28	24	52	53	53	53	53
	En	42	55	34	38	38	38	47
	Fs	30	21	14	9	9	9	...

Note: Based on Nockolds [41] 1954. I. Tholeiitic basalts (average of 137). II. Tholeiitic olivine basalts (average of 28). III. Alkali basalts (average of 96). IV. Olivine-rich alkali basalts (average of 31). V. Ordanchite (average of 27). VI. Nepheline tephrite (average of 8) VII. Analcite tephrite (average of 7).

# INTERNATIONAL GEOLOGY REVIEW

TABLE 4A. The chemical composition of the volcanic rocks of east Otago, New Zealand and Uganda, South Africa

Rock type Composition	a	b	c	d	e	f
SiO <sub>2</sub>	43.03	47.1	48.34	52.37	57.88	45.59
TiO <sub>2</sub>	2.66	2.3	2.20	1.27	1.55	3.11
Al <sub>2</sub> O <sub>3</sub>	13.82	14.7	16.14	18.49	18.07	14.43
Fe <sub>2</sub> O <sub>3</sub>	3.70	3.5	3.43	2.53	2.22	2.87
FeO	8.95	9.0	9.80	5.17	2.54	8.42
MnO	0.21	0.2	0.23	0.23	0.11	0.17
MgO	8.59	8.7	3.16	2.34	0.83	8.51
CaO	9.23	10.2	6.54	5.25	3.94	9.16
Na <sub>2</sub> O	3.91	3.1	5.24	5.47	5.77	2.57
K <sub>2</sub> O	2.14	0.9	2.01	3.20	3.94	3.48
P <sub>2</sub> O <sub>5</sub>	0.73	0.3	1.50	0.46	0.56	0.65
H <sub>2</sub> O	3.15	...	1.07	2.65	1.79	0.74
Other	0.23	...	0.42	0.30	0.15	0.49
Q	-16.57	-7.34	-8.67	-6.15	2.10	-11.75
Or	12.25	5.56	11.68	18.90	48.73	20.57
Ab	8.91	23.32	33.01	37.73	48.73	8.12
An	13.91	23.35	14.73	16.40	12.23	17.51
Ne	13.06	1.56	5.96	4.54	...	7.24
Di	22.18	20.64	10.73	5.27	3.08	19.43
Hy	...	...	...	...	0.93	...
Ol	14.32	15.77	10.62	6.52	...	14.53
Mt	5.34	5.10	4.87	3.71	3.25	4.18
Il	5.17	4.41	4.26	2.43	2.89	5.72
Ap	1.66	0.67	2.02	1.34	1.34	1.34
Wt% { Or	35	10	19.5	26	27	44
Ab	25(39)	45(50)	55.5(68)	52(70)	58(80)	18
An	40(61)	45(50)	25.0(32)	22(30)	15(20)	38
Wt% { Wo	52	52	50	51	40	52
En	33	53	20	25	50	34
Fs	15	15	30	24	10	14

Note: Rock type -- a - Nepheline basanite. b - Olivine basalt [Rev. Note: Turner and Verhoogen [91] 1951, p. 144, Table VIII; averages of analyses 3-10 in Benson [42] 1942, p. 113, table V.] c - Oligoclase basalt of Benson [42], 1942. d - hornblende trachybasalt. e - pyroxene trachyandesite of Benson and Turner [43], 1939. f - leucite basanite of Holmes and Harwood [44], 1937 (J & L, new average).



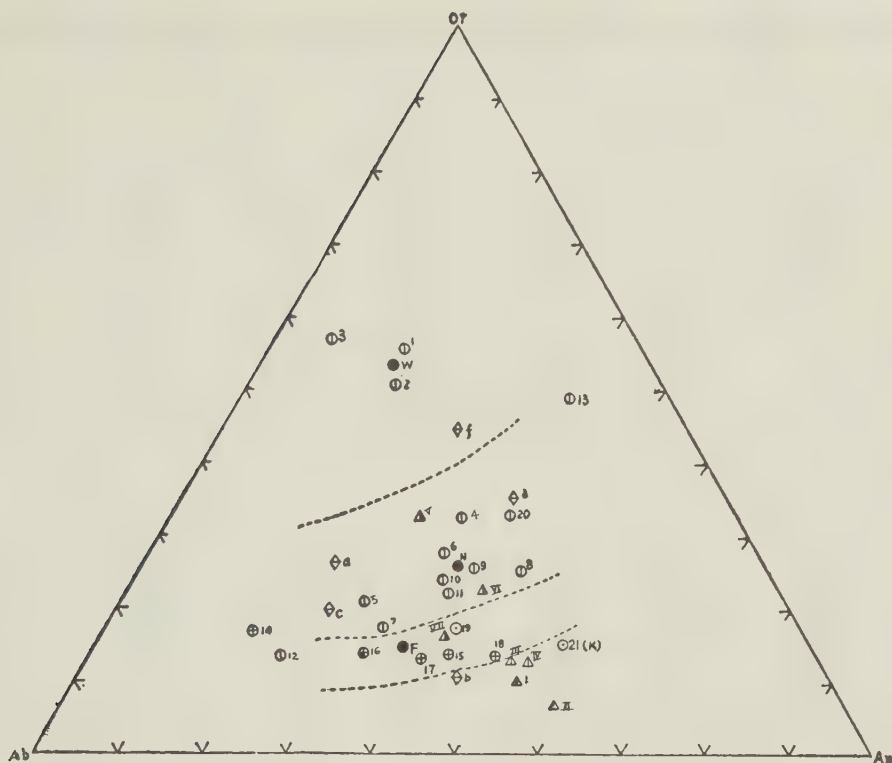


FIGURE 2. Normative feldspar composition of the basalts of eastern China (in weight percent)

- Basalts of various parts of China (⊙ with normative nepheline, ⊕ with normative quartz). 1, 2, 3, . . . refers to localities as shown in Table 2A.
- △ Types of basalts of the world (△ with normative nepheline, ▴ with normative quartz, ▴ with normative feldspathoid), I, II, III, . . . same as in Table 3A.
- ◇ New Zealand type basalt (◇ with normative nepheline), a, b, c, . . . as in Table 4A
- Average basalts of various Chinese regions. W, N, F, . . . same as in Table 2A.

The pyroxenes of basalts of northern Manchuria and of northern China and southern Manchuria are rich in the wo molecule (nos. 1-13, table 2A) and resemble the alkali-basalt and feldspathoid basalt of the world (III, IV, V). Some basalts of southern China (nos. 15 and 19) are poor in fs and rich in en. This would indicate that the basalts of northern China and southern Manchuria are higher in alkalis and poor in silica. Large amounts of olivine crystallized, removing Fe and Mg from the melt, so that the pyroxenes were relatively enriched in wo. Tomita [56], in the discussion of the pyroxenes of igneous rocks, pointed out that the composition of augite of the calc-alkalic rocks does not cross the Di-Hd line or lie within the Wo-Di-Hd region. They scatter between en 30-50 percent and are related to pigeonite. On the other hand, augites of the alkali-basalt, although some are close to pigeonite in composition, are soda-rich. They are generally rich in wo, and the composition crosses the Di-Hd line and lies within the area of Wo-Di-Hd. K Yagi [47] described the norma-

tive pyroxene composition of the alkali basalt of Sakhalin which lies near the Di-Hd line but is outside the Wo-Di-Hd region. Thus, except the basalts of Kuan-yin-shan of Taiwan and Hainan Island, the basalts of eastern China, according to their normative composition, belong to the alkali basalt type (Tables 2B, 3B, and 4B)

#### Variation of the Niggli values

The Niggli values calculated from the average chemical composition listed in Table 2A are shown in Table 2B. The si values of the basalts of eastern China range from 88-132, three-fourths of which lie between 100-130, and one-third lie between 120 and 130. The value of al ranges from 15 to 25, about one-half lie between 2-25. fm ranges from 17 to 26, four-fifths of which lie between 40-50 and about one-half lie between 20-25. alk ranges from 8 to 20, about one-half of which lie between 10-15. The value of k ranges from 0.14 to 0.50, about one-third of which lie between 0.2-0.3. The value of mg ranges

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TABLE 3B. Niggli and Zavaritsky's value of various types of basalts of the world

Rock types Niggli-values	I	II	III	IV	V	VI	VII
Si	122.8	96.0	97.2	77.9	113.5	98.0	92.4
al	20.0	14.0	18.3	9.4	23.5	19.8	20.4
fm	46.7	62.0	50.6	70.0	37.9	43.0	46.2
c	26.9	20.6	24.5	17.3	22.2	24.2	20.9
alk	6.4	4.0	6.6	3.3	16.4	13.0	12.5
mg	0.49	0.68	0.59	0.73	0.47	0.55	0.41
k	0.20	0.18	0.19	0.22	0.25	0.14	0.22
al-alk	13.6	10.0	11.7	6.1	7.1	6.8	7.9
C-(al-alk)	13.3	10.0	12.8	11.2	15.1	17.4	13.0
qz	-2.8	-20.0	-29.2	-33.3	-52.1	-54.0	-57.5
Rock types Zavaritsky's values	I	II	III	IV	V	VI	VII
a	5.1	4.2	7.0	4.3	15.5	13.3	13.3
c	6.4	5.3	6.1	4.0	3.3	3.5	4.2
b	28.1	35.8	33.5	53.3	25.1	30.9	31.5
s	60.4	54.7	53.4	38.4	56.1	52.8	51.0
f'	40.0	26.6	32.9	23.0	37.5	39.1	45.8
m'	38.0	59.3	46.8	63.3	34.0	32.2	32.3
c'	22.0	14.1	20.3	13.7	28.5	28.7	21.9
n	80.0	82.0	80.8	77.4	74.5	85.8	77.6

Note: rock types I, II, III . . . are the same as in Table 3A.

TABLE 4B. Niggli and Zavaritsky's value of the Cenozoic volcanic rocks of east Otago, New Zealand

Rock types Niggli-values	a	b	c	d
Si	92.8	101.4	125.8	156.0
al	17.5	18.6	24.7	32.4
fm	50.3	50.0	40.7	29.2
c	21.3	23.5	18.2	16.6
alk	10.9	7.9	16.4	21.8
mg	0.55	0.54	0.3	0.35
k	0.25	0.15	0.2	0.28
al-alk	6.6	10.7	8.3	10.6
C-(al-alk)	14.7	12.8	7.9	6.0
Qz	-50.8	-30.2	-39.6	-31.2
Rock types Zavaritsky's values	a	b	c	d
a	11.5	8.0	14.8	17.4
c	3.4	5.5	3.7	4.2
b	34.0	32.3	22.9	14.4
s	51.1	54.2	58.6	64.0
f'	34.6	35.6	55.9	53.5
m'	42.6	44.4	24.1	29.0
c'	22.8	20.0	20.0	17.5
n	74.1	83.8	80.0	72.1

NOTE: Rock types a, b, c, d, same as in Table 4A.



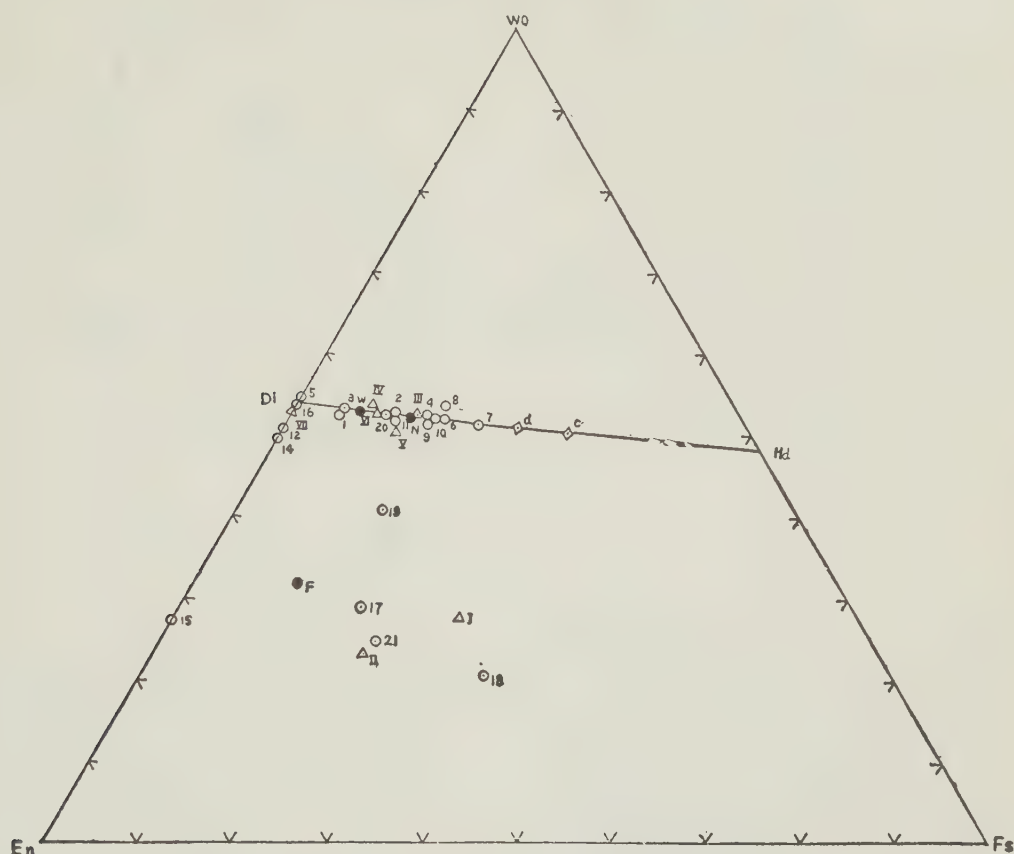


FIGURE 3. Normative pyroxene composition of the basalts of eastern China (in weight percent)

○ 1, 2, 3, . . .    △ I, II, III, . . .    ◇ a, b, c, . . . same as in Figure 2.

from 0.33 to 0.68 about two-fifths lie between 0.5-0.6. The chemical characteristics of the basalts of eastern China, however, show that alk is greater than 10 and is closer to alkali basalt instead of normal basalt. Briefly, the types of basaltic magma of eastern China are tabulated as follows:

to the gabbro type of calc-alkalic series of the Pacific province. The composition of the basalts of eastern China as a whole, not including that of Kuan-yin-shan of Taiwan, resembles that of the sodic-gabbro type of the Atlantic province. Clearly, the magma types of basalts of eastern China show distinct regional variations.

Region	si	al	fm	c	alk	k	mg	Magma type
Northern Manchuria (W)	130.0	21.0	44.0	18.0	17.0	0.49	0.59	Lamprosommatitic
Northern China (N)	101.0	19.5	47.2	22.2	11.1	0.25	0.52	Nepheline syenite-gabbroic
Southern China (F)	122.5	22.6	43.9	22.9	10.6	0.21	0.45	Syenite gabbro-dioritic
Taiwan (K)	119.0	26.0	42.0	24.0	8.0	0.30	0.60	Syenite gabbro-mihraraitic
Eastern China (C)*	111.8	20.6	46.0	21.5	11.9	0.31	0.53	Nepheline syenite-gabbro-dioritic

\* Includes the alkali basalt of Hsin-chu of Taiwan.

According to Niggli's classification of magma types, the basalts of southern China belong to the gabbro-diorite type of the calc-alkalic series of the Pacific province. Basalts of northern China belong to the sodic gabbro type of the sodic rock series of the Atlantic province. Basalts of northern Manchuria belong to the potash diorite type of the potassic rock series of the Mediterranean province. Basalts of Taiwan belong

#### Variation of the Niggli $qz$ values

Based on the values in Table 2B, the Niggli  $qz$  values of the basalts of eastern China were plotted in Figure 4 with si the abscissa and  $qz$  the ordinate. For comparison, the  $qz$  values of various basalts of other parts of the world (Tables 3B and 7B) were also plotted on the same diagram.

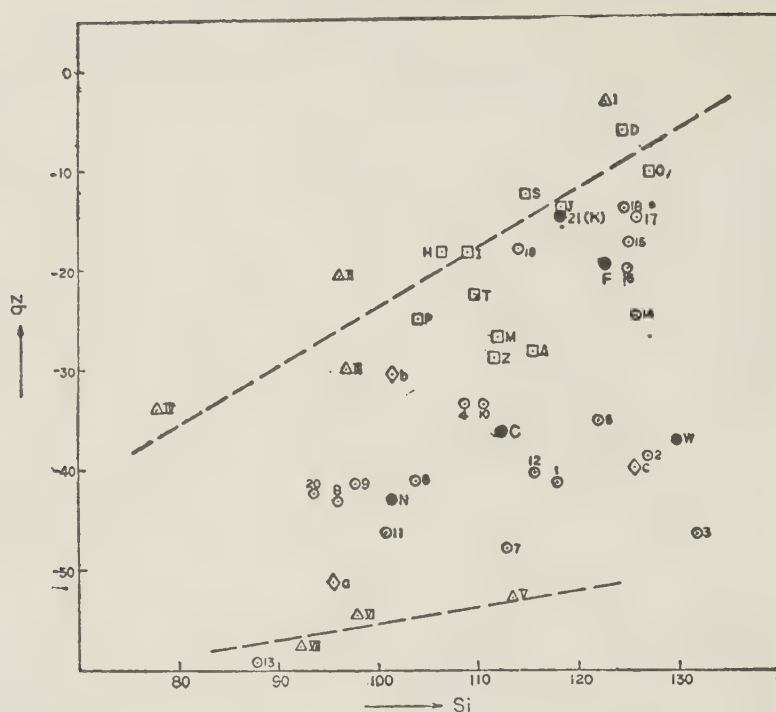


FIGURE 4. Diagram showing the Niggli  $qz$  values of the basalts of eastern China.

- Basalts of various parts of China. 1, 2, 3 . . . and F, N, W, . . . same as in Figure 2.
- △ Various types of basalts of the world. I, II, III . . . are the same as in Figure 2.
- ◇ Basalts of New Zealand, a, b, c . . . are the same as in Figure 2.
- Basalts of various parts of the world. I, D, S . . . are the same as in Table 7A.

The plot shows that all the  $qz$  values of basalts of eastern China have relatively low negative values. The  $si$  values of basalts of southern China (nos. 14-19, table 2B) are comparable to those of Indonesia (I), India (D), and North America (O) but the  $qz$  values are lower. The  $qz$  values of the basalt of Kuan-yin-shan of Taiwan is similar to that of Japan (J). The  $qz$  of the rest of eastern China are even lower than the alkali basalts of New Zealand (Z), the Circum-Japan Sea (A), and Sakhalin (M). Their  $si$  values, however, are mostly greater greater than the alkali basalts of the world (III-IV). As a whole the  $qz$  values of the basalts of eastern China are low and lie between line I-IV (normal basalts) and V-VI (feldspathoid-bearing basalt) which are similar to the alkali basalts (a, b, c) of East Otago, New Zealand. Furthermore, the  $si$  and  $qz$  values of basalts of various parts of China are concentrated in certain parts of the diagram, especially those of southern China in contrast to those of northern Manchuria. Since the Niggli  $qz$  value is equal to  $si-si'$ , which is directly related to the alk value, and since the alk of the basalts of eastern China also have

high values, correspondingly the  $qz$  values would therefore be low. The  $qz$  value which reflects a high alk value indicates that the basalts of eastern China are alkali basalts.

#### Variation of the Niggli $al-alk$ values

Figure 5 shows the  $al-alk$  values of the basalts of eastern China. Except no. 15 (Fangshan of Nanking), no. 18 (Hainan Island) and no. 21 (Kuan-yin-shan of Taiwan), the  $al-alk$  value of most basalts are lower than those of the normal basalts of the world (below the IV-I dashed line). Many are scattered between line IV-I and line joining V and VI representing feldspathoid-bearing basalt similar to the alkali basalts of East Otago, New Zealand (a, b, c) but some are even below line V-VI, for example nos. 1-3 and nos. 12-14. The clustering of the points of a particular region is also evident, particularly those of southern China and northern Manchuria. Because the variation of the  $al-alk$  value is reflected by the normative  $an$  composition, Figure 5 also directly reflects the variation of normative  $an$ . The basalts of Kuan-yin-shan of Taiwan, Hainan



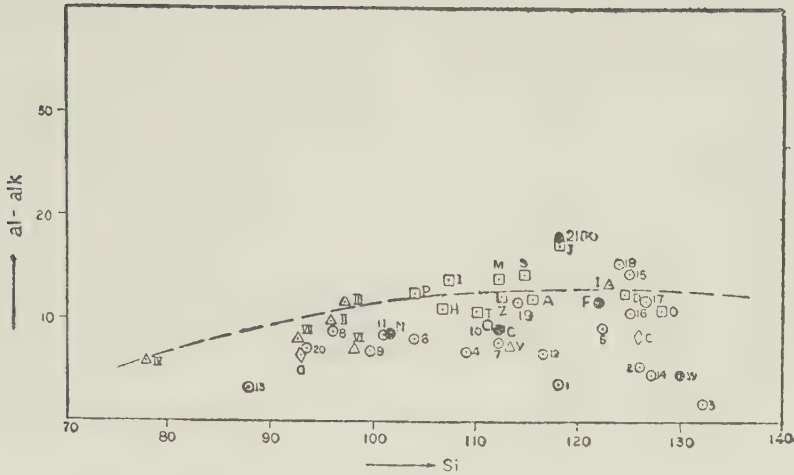


FIGURE 5. Variation of  $\underline{\text{al-alk}}$  values of the basalts of eastern China

○ 1, 2, 3 . . . □ S, J, D . . . ● W, N, F . . . refer to localities and △ I, II, III . . . ◇ a, b, c, . . . to rock types as shown in Figure 4.

Island, and Fang-shan of Nanking are higher in  $\underline{\text{an}}$  and those of P'u-chen, Shantung, Ching-ching and northern Manchuria are lower in  $\underline{\text{an}}$ . Basalts of other areas are also lower in  $\underline{\text{an}}$  than those basalts of the world. This means that the basalts of eastern China are higher in alkalis; the plagioclase is more sodic, therefore, more typical of the alkali basalts.

#### Variation of the Niggli $\underline{\text{c-(al-alk)}}$ values

Figure 6 shows the variation of the  $\underline{\text{c-(al-alk)}}$

values of the basalts of eastern China. Except no. 21, (Kuan-yin-shan of Taiwan), no. 18 (Hainan Island) and no. 15 (Fang-shan of Nanking) the  $\underline{\text{c-(al-alk)}}$  values of Cenozoic basalts of other areas of China are higher than the normal basalts of the world (dashed line). Most of the values lie between I, the normal basalts, and VI, the nepheline basalts of the world. The clustering of points is again evident for those of southern China and northern Manchuria. Since the  $\underline{\text{c-(al-alk)}}$  value is related to the normative  $\underline{\text{wö}}$  content; and the normative

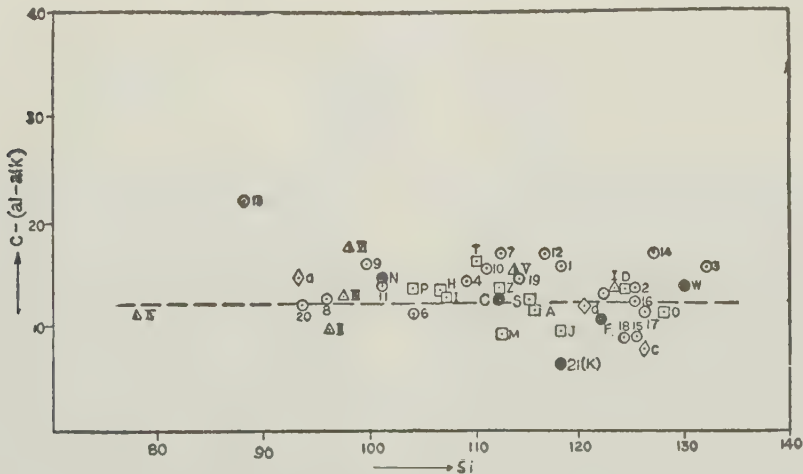


FIGURE 6. Variation of the Niggli  $\underline{\text{c-(al-alk)}}$  values of the basalts of eastern China

○ 1, 2, 3 . . . △ I, II, III . . . □ S, I, D . . . refers to localities, same as those of Figure 4. ◇ a, b, c . . . ● W, N, F . . . refer to rock types same as in Figure 2.

wo value is in sharp contrast between alkali-basalts, and basalts that are not alkalic, thus because of the high alkali contents of the basalts of Manchuria, northern China, Inner Mongolia and P'u-chen (nos. 1-14, table 2A) their  $c(\text{alk})$  values are also high. This means that the normative pyroxene composition is rich in wo, even higher than the alkali basalt of New Zealand (a, b, c). Evidently the basalts of eastern China belong to an alkalic series.

#### Variation of the Niggli $k$ -mg values

Figure 7 shows the variation of the  $k$ -mg values of the basalts of eastern China. Most of

as no. 7 (Ying-o-men of Liaoning), no. 5 (Pai-t'ou-shan of Kirin), no. 14 (P'u-chen of Kiangsu), and no. 18 (Hainan Island) are comparable to those of the normal basalts of the world, but higher than some alkali basalts of New Zealand (c, d). In most alkali basalts, MgO values are low and FeO are high, which is also the case for basalts of eastern China.

#### Zavaritsky's Petrochemical Diagrams

Figure 8 shows the variation of the Zavaritsky value [57] of the basalts of eastern China. In the alkali part of the diagram, the alkali atomic index of the basalts of eastern China are greater

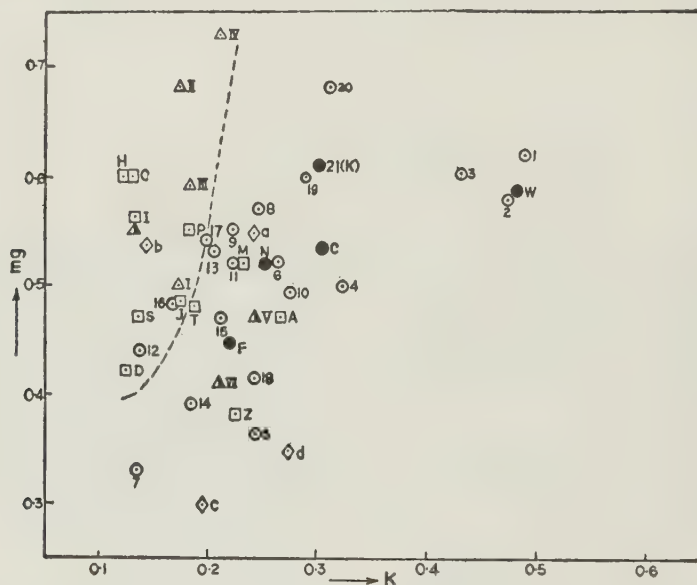


FIGURE 7. The variation of the Niggli  $k$ -mg values of basalts of eastern China.

○ 1, 2, 3 . . . □ H, 0, 1 . . . ● C, N, F . . . refer to areas same as those in Figure 4. △ I, II, III . . . ◇ a, b, c . . . refer to rock types same as those in Figure 2.

them show relatively high  $k$  value particularly those of northern Manchuria (nos. 1-3), and Mu-leng (no. 4), Wei-ch'ang (no. 10), Pai-t'ou-shan (no. 5), Hainan Island (no. 18), Wei-chou-tao (no. 19) and Taiwan (nos. 20-21). The  $k$  values of basalts of other areas are also in excess of 0.2, so that the  $k$  values of basalts of northern China, southern Manchuria, southern China and Taiwan are greater than those of average normal basalts of the world (line IV-I in Figure 7). The normative feldspar composition and the  $qz$  values of the basalts of Hainan Island and of Kuan-yin-shan of Taiwan are similar to those of the normal basalts of the world, except that their  $k$  values are clearly higher. This is the characteristic chemical composition of the basalts of eastern China. The  $mg$  values of these basalts are, in general, moderately low. Those with low  $mg$  values such

than those of the average normal tholeiitic basalt (I), the tholeiitic olivine basalt (II), and the normal alkali basalt (III), but smaller than other feldspathoid-bearing basalts (V, VI, VII). According to the values on page 349 of Zavaritsky's book on the petrochemical study of igneous rocks [57], the Chinese basalts are similar in the alkali atomic index to those of the alkali basalts of New Zealand (a, b, c). In the calcium part of the diagram, the variation of the atomic index of calcic feldspar covers a rather large area. No. 15, (Fang-shan of Nanking), no. 18 (Hainan Island) and no. 21 (Kuan-yin-shan of Taiwan) have high indices whereas those of northern Manchuria (nos. 1-3) and P'u-chen (no. 14) have low indices. Both of these plots lie outside of the plot for the normal basalt and feldspathoid basalt of the world. The atomic index of calcic feldspar of other Chinese basalts is, in general, similar



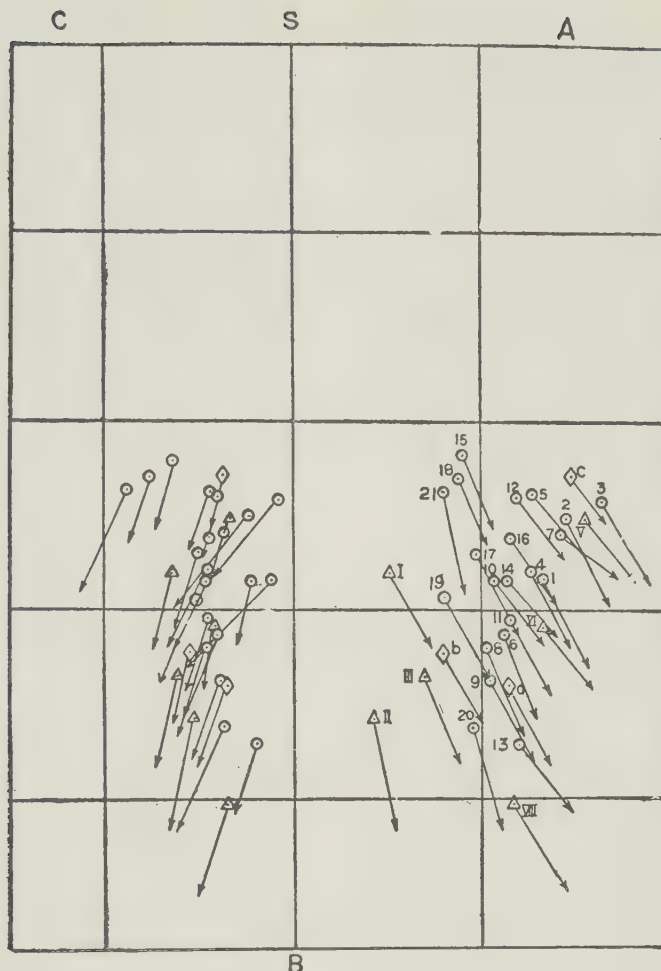


FIGURE 8. Variation of the Zavaritsky value of the basalts of eastern China

① 1, 2, 3 refers to localities same as in Figure 2.

▽ average composition of various basalts of the world I, II, III . . . same as in Figure 2. ◇ a, b, c . . . refers to types of basalts of New Zealand, same as in Figure 2.

[Tr. Note: Point VIII in Figure 8 not included in Tables 3A and 3B, is that of a nepheline basalt; source not indicated but probably also from Nockolds [41].]

to that of basalts of New Zealand. In the silica atomic index part of the diagram, not only are the values of most of them higher than those of the tholeiitic olivine basalt (II) and alkali basalt (III), but also about half of them have values higher than the normal tholeiitic basalt (I). In contrast, the iron-magnesium atomic indices are largely lower than those for the alkali-basalt (III) and tholeiitic olivine basalt (II). Thus the basalts of eastern China are high in alkalis and silica. Regionally, the basalts of northern Manchuria are highest in alkalis (nos. 1-3), next are those of northern China and southern Manchuria (nos. 4-13). Those of southern China are low (nos. 14-19). The basalts of northern China

and southern Manchuria (nos. 1-3) are lowest in silica, next are those of southern China (nos. 14-19), and highest for those of northern Manchuria (nos. 1-3). This type of relationship is shown most clearly by the Zavaritsky diagram. Based on figures in Table 2B and  $Q = S - (3a + 2c + b)$ , the  $Q$  value of the basalts of Taiwan is  $-6$ , with  $a:c = 0.9$ , equivalent to silica-saturated, weakly alkalic rocks. The basalts of southern China have  $Q = -8.1$  and  $a:c = 1.8$ , or silica-saturated, weakly alkalic types. The basalts of northern China and southern Manchuria have  $Q = -19.6$ ,  $a:c = 2.7$ , or silica-undersaturated, alkalic rocks. The basalts of northern Manchuria with  $Q =$

-1.54 and  $a:c = 7.3$  are silica-undersaturated, strongly alkalic rocks. This shows the striking regional variation of silica saturation and alkalinity of the basalts of China. Their individual characteristics are shown by the clustering of plots of the chemical composition of basalts of these regions. In the alkali composition part of the diagram, the vector of the supplementary index shows that the basalts of Taiwan (nos. 20-21) are highest in MgO. Those of northern China and southern Manchuria, especially that of Ying-o-men (no. 7), Wei-ch'ang (no. 10) and Shantung (no. 13) contain high amounts of CaO, indicating that the ferromagnesian minerals, such as pyroxene, are highly calcic. This is the same as shown by the high normative wollastonite content of the rock high in alkalis. In the calcium composition part of the diagram, the basalts of northern Manchuria (nos. 1-3) show clear increase in  $K_2O$ .

#### The Relation between the Chemical Composition and the Modal Mineral Composition

From the description above, on the basis of either the mineral composition or the chemical composition, the basalts of eastern China as a whole, besides their regional variation, are high in alkalis and silica. This is reflected by the more acid composition of the plagioclase co-existing with the ferromagnesian minerals. Moreover, because of the strong differentiation, nepheline basalts occur locally. The  $K_2O$  content is generally high. This is not only indicated by the high normative or composition, but also by the occurrence of modal anorthoclase in basalts of Wei-chou Island of southern China [37]. In northern China and southern Manchuria, potassic andesine occurs in the basalt. Because of the excessive  $K_2O$  content, the basalts of northern Manchuria and of Hsin-chu of Taiwan contain leucite. The basalts of southern China with high  $SiO_2$  and low MgO, shown by the presence of normative quartz and hypersthene, are of the silica-saturated type. Although these rocks are also relatively high in alkalis, oligoclase and occasionally anorthoclase occur only in the groundmass. The basalts of northern China and southern Manchuria contain less amount of  $SiO_2$  and higher amount of alkalis, so that they contain normative nepheline and olivine; therefore they belong to the undersaturated type. Not only is plagioclase more acid, but, in addition, potassic andesine and anorthoclase are present. Chemically basanitoid and tephritoid basalts as well as nepheline basalts occur. The basalts of Manchuria are highest in alkalis, with  $K_2O$  greater than  $Na_2O$ , and accompanied by a rather high  $SiO_2$  content. The rocks have normative nepheline, leucite and olivine; therefore, the rock type is undersaturated. These rocks contain modal leucite and biotite. The basalts of Kuan-yin-shan of Taiwan are typically tholeiitic basalts, on the basis of the chemical and normative mineral

composition and their associated rock types. But the basalt of Hsin-chu in the adjoining area, is clearly an alkalic basalt which contains analcite and leucite. The basalts of eastern China show gradual regional variation with respect to their chemical composition and their magma type. For example, the highly alkalic basalt of P'u-chen in southern China and the highly potassic basalts of Mu-leng and Shuang-liao of southern Manchuria, the latter containing leucite, are all closely related chemically to the associated rock types with lesser alkali or potassium content. In Manchuria, the alkali content of basalts increases geographically towards the direction of the continent. Kuno [58] described the aphanitic tholeiitic basalt of Tungning along the Usuri River, the mineral composition of which is similar to the basalts of Japan. The basalts of Mu-leng, Pai-t'ou-shan and Ching-yü are trachyandesitic olivine basalts often containing potassic andesine and anorthoclase, whereas those of Te-tu, K'e-tung, Shuang-liao, and Ch'ing-yuan of central Manchuria are feldspathoid basalts, such as leucite basanites and nepheline basalts. This shows the progressive increase of alkalis in basalts from the sea towards the continent.

In southern China, according to Ch'en Yuchi and Shen Yung-ho [26] the basalts of Fangshan show trend of variation from olivine basalt to tholeiitic basalt. The lower basalt of Fangshan (no. 41, olivine basalt, table 1) represents an olivine basalt, either on the basis of  $SiO_2$ , or the ratio of  $MgO/CaO$  or  $MgO/FeO$ . The upper basalt of Fangshan (no. 46, tholeiitic basalt, table 1) chemically represents a tholeiitic basalt. The transitional phase represents differentiation. Mineralogically the early basalt contains only olivine, whereas the late stage basalt contains labradorite phenocrysts, indicating that they are petrogenetically related. Tomita [45], who observed the occurrence of quartz basalt along the contact between olivine basalt and hypersthene andesite such as at Shan-ying of Japan, postulated that tholeiitic basalt can be derived from olivine basalt by the assimilation of siliceous material. As described above, hypersthene basalt and quartz basalt both occur on Hainan Island of southern China. The author (1949) also observed corroded quartz grains in a basalt collected by Tung Nan-ting from the vicinity of Niu-shou-shan of Nanking. The corroded quartz is surrounded by a brownish glassy reaction rim, associated with clusters of fine-grained interstitial pyroxene. Therefore, there is evidence of the assimilation of sediments by olivine basalts of Hainan Island, and in the vicinity of Nanking. Thus,  $SiO_2$  and  $Al_2O_3$  increase in the late stage of the basalt magma giving it the tholeiitic characteristics. Chemically, the basalts of northern China and southern Manchuria are alkalic. In addition to large amounts of olivine, titanite and relatively acid plagioclase, the rock often contains potassic andesine and anorthoclase filling



the space between the plagioclase. They have been observed in basalts of Pai-t'ou-shan and Ching-yu of Kirin and Wei-ch'ang and Ching-Ching of Hopei and Ling-yuan of Liaoning. The author (1950) also observed potassic andesine filling the space between plagioclase with irregular replacement texture in an olivine basalt collected from the vicinity of Hua-tien of Kirin. The twinning of the potassic andesine is indistinct. It was wavy extinction, with  $\beta = 1.550_{\pm}^{+}$ ,  $(+)$ ,  $2V = 45_{\pm}$  and commonly with apatite inclusions and rimmed by anorthoclase. The small optic axial angle is characteristic of this mineral. It is not the result of the orientation of the thin section parallel to (010), or to the interference effect of twinning. This type of reaction has been noted by Mountain [59] who considered it as a solid solution series of

andesine and anorthoclase. Not only is potassic feldspar found time and again from eastern China, Macdonald [60] also described potassic plagioclase from the basalts of Hawaii. Kuno [92] in 1940 also found potassic andesine and potassic oligoclase in andesites and in xenoliths of Hakone volcano, Japan. The potassic oligoclase shows continuous gradation to anorthoclase. Thus the occurrence of potassic andesine and anorthoclase should be quite widespread in basalts of northern China and southern Manchuria, which also accounts for the high  $K_2O$  content. The total alkalis of basalts of northern Manchuria are even higher, with  $K_2O$  greater than  $Na_2O$ , so that there are leucite basalts. Nonetheless, these basalts contain abundant biotite which is also characteristic of the basalts of northern Manchuria.

(Part 2 of 2 will appear in the April issue of IGR)

# APPLICATION OF 'FOCAL SCREENING' TO MEASUREMENT OF INDICES OF REFRACTION BY THE IMMERSION METHOD<sup>1</sup>

by

Yu. A. Cherkasov

• translated by Ivan Mittin<sup>2</sup> •

## ABSTRACT

A parallel ray-bundle of white light, crossing the solid/liquid boundary at a small angle, is spread into a spectrum when the index of the immersion liquid approaches that of the solid. This is due to the greater dispersion of liquids and forms the basis of the three variants of the "focal screening" method, using appropriate masks in the focal plane of the objective: (1) In apertural screening the ray-bundle is parallel to the microscope axis, and an iris diaphragm in the focal plane of the objective is restricted until only the undeviated wavelengths pass. Thus at the grain edges only the color for which the index of liquid and solid match is seen. (2) In unilateral screening the ray-bundle is inclined and the diaphragm is restricted to block certain of the rays and reveal different colors on opposite edges of the grain. (3) In central screening the ray-bundle is again parallel to the microscope axis, and a dot mask at the center of the focal plane holds back the undeviated rays. The edge color is a recognizable combination of those of the deviated rays.

Indices are said to be measurable to .001 with the first arrangement, more accurately with the second, and "more accurately than by the Becke method" with the third. Advantages include the benefits of chromatic variation without requiring a variable monochromator, visibility of grains at the match point, and less disturbance by inclusions. The effectiveness of this method is increased by quantitative data on the dispersion of the liquids. -- R. E. Wilcox.

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<sup>1</sup>Translated from O primeneni "fokalnogo ekranirovaniya" pri izmereniyakh pokazateley prelomleniya immersionym metodom: Sovremennyye metody mineralogicheskogo issledovaniya gornyykh porod, rud, i mineralov [Modern methods of mineralogic investigation of rocks, ores, and minerals], E.V. Rozhkova, Ed., Gosudarstvennoye Nauchno-tekhnicheskoye Izdatelstvo Literatury po Geologii i Okhrane hedr, Moscow, p. 184-207, 1957. Edited by Ray E. Wilcox, U.S. Geological Survey, Denver. Published with permission of the Director, U.S.G.S.

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## Introduction

As is known, in measuring the index of refraction of any solid, transparent substance by the immersion method, this finely crushed substance is placed in a liquid of known index of refraction. The specimen thus prepared is examined microscopically in transmitted light. Depending on the relation of indices of refraction of the substance investigated and the liquid used, as well as on the method of illuminating

the specimen, one may detect on the investigated grains (under certain conditions) effects which permit judging of this relation.

There are several methods which use comparison of the indices of refraction of the substance under investigation with that of the immersion liquid. We will not dwell on the description of these methods, assuming they are well known; we need only note that none of these methods fully realizes all those possibilities which are revealed, both by the apparatus which is used in investigations of this type, and by the phenomena which are displayed during the transmission of light rays through the immersed specimen, especially working with white light. The proposed method of "focal screening" in our opinion, fills this gap to a considerable degree.

Refraction of the ray bundle in  
grains of the immersed specimen.  
Angular dispersion.

As stated above, the immersed grains of the investigated substance are finely divided. The shape of grains can vary greatly, and they seldom have strict geometrical outlines. In the majority of cases they are bounded by numerous refracting surfaces inclined at different angles to the microscope axis, with the sections of the grains nearest to the margins generally having the greatest refractive angles, and the sections at the middle of the grains having the smallest angles.

If the immersed specimen is placed on the microscope stage and the parallel bundle of rays is directed to it, then, with any difference of refractive indices between the investigated substance and immersion liquid at the refracting surfaces of the grain, the rays of this bundle deviate from their original direction according to the law of Snell-Descartes. Let

us assume (fig. 1) that a light ray travels in the direction AB to some refractive surface of the grain at the point O. If the refractive index of the substance under investigation is  $N_1$  and of the liquid  $N_2$ , and the angles of incidence and refraction are respectively  $\alpha$  and  $\beta$ , then, following the law of refraction, we may write:

$$N_1 \sin \alpha = N_2 \sin \beta \quad (1)$$

Replacing  $\sin \beta$  in equation (1) by its equivalent value,  $\sin(\alpha + \theta)$ , where  $\theta$  is the angle of deviation of the ray from its original direction, we obtain:

$$N_1 \sin \alpha = N_2 \sin(\alpha + \theta) \quad (2)$$

Formula (2) can be applied to the calculation of angle  $\theta$  at any values of  $N_1$  and  $N_2$ , that is, at any values of the difference  $(N_1 - N_2)$ .

In calculating the angle of deviation of rays from the original direction for small differences of the indices of refraction of the two media, the formula (2) can be rewritten as follows:

$$\Delta\theta = \frac{\Delta N}{N_{av}} \tan \alpha \quad (3)$$

where  $\Delta N = N_1 - N_2$ , the difference of indices of the two media, and  $N_{av} = \frac{N_1 + N_2}{2}$ , the average index of refraction.

From the law of refraction it follows that when the indices of refraction of two media are equal, the angular deviation  $\theta$  equals zero. In such case the ray bundle will travel through the refracting surfaces of the grain without deviation from the original direction (see fig. 1B). Because of the different dispersions of the solid and liquid media, this phenomenon in white light can only take place for rays of a particular wavelength. Rays of another wavelength will deviate from their original direction by an angle determined by the formula:

$$\Delta\theta = \frac{\Delta D}{N_{av}} \tan \alpha \quad (4)$$

where  $\Delta\theta$  = value of the angular dispersion  
 $\Delta D$  = difference of the specific dispersions of the two media.

Knowing the values of specific dispersions of the mineral and liquid used, one can determine by equation (4) the angle  $\theta$ , by which the ray of white light is opened into the spectrum in falling on the refracting surface (fig. 2).

These calculations were carried out by us for different indices of refraction on the basis of the published data on the value of the mean dispersion ( $\Delta D_{F-C}$ ) of minerals and immersion liquids. The average values of angular dispersion  $\Delta\theta_{F-C}$  for the same interval obtained for wavelengths on the surfaces with refractive angles 80-85° are given in Table 1.

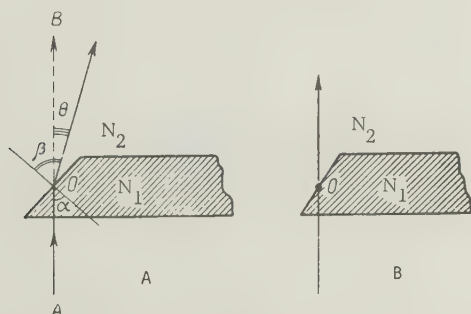


FIGURE 1. Passage of a monochromatic ray through the refracting surface of a crystal.  
A. For  $N_1 < N_2$       B. For  $N_1 = N_2$

<sup>3</sup> Ed: Use of  $\Delta\theta$  here and later in the text is not consistent with the figures. Could  $<\theta$  or  $\angle\theta$  be méant?



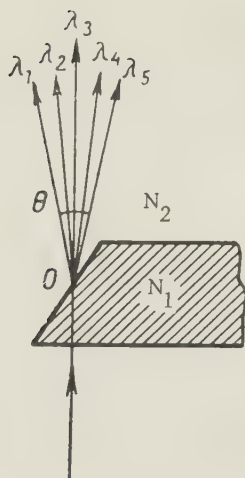


FIGURE 2. Dispersion of a ray of white light in passing the refracting surface of a crystal. Indices of refraction of the two media coincide for  $\lambda_3$ .

TABLE 1. Average angular dispersion ( $\Delta\theta_{F-C}$ ) for different indices of refraction

Indices of refraction	$\Delta D_{F-C}$	$\alpha = 80^\circ$	$\alpha = 85^\circ$
1.4 to 1.5	.001 to .006	15' to 1°	30' to 2°
1.5 to 1.6	.006 to .012	1° to 2°30'	2°30' to 5°
1.6 to 1.7	.012 to .017	2°30' to 3°	5° to 6°30'
1.7 to 1.8	.017 to .025	3° to 4°	6°30' to 9°

The Table shows that the magnitude of the angular dispersion increases along with the increase of the index of refraction, and that it can attain large values with nearly vertical refractive surfaces. In case the indices of refraction of the two media coincide for a certain wavelength of visible light, the spacial diversion of rays of other parts of the spectrum with such surfaces becomes so significant that it can be utilized for practical purposes, as will be shown later.

The angular dispersion takes place also when the differences of indices of refraction of the two media are great, but in that case its value will be small, in conformance with formula (3), because the values ( $\Delta n$ ) for different wavelengths will differ but slightly.

Linear deviation of rays on the rear focal plane of the objective.  
Linear dispersion.

Any angular deviation of ray bundles from their original direction will be indicated on the back focal plane of the objective by their linear deviation. For small values of  $\Delta\theta$  this linear

deviation can be determined from formula:

$$\Delta X = \theta \cdot f \quad (5)$$

where  $\Delta X$  = the linear deviation of a ray on the focus plane of the objective

$\Delta\theta$  = the angular deviation from the original path

$f$  = focal distance of the focusing system (fig. 3).

It is evident from formula (5) that the linear deviation of a ray from its original path at the same value of  $\Delta\theta$  is the greater, the longer is the focal length of the objective.

Employing the data of table 1 and formula (5), it is possible to draw a picture of the linear dimensions of the spectrum formed on the back focal plane of the objective by a ray of white light. By placing a screen in this plane in a certain manner, it is possible to hold back practically all the rays with linear dispersion not equal to zero: that is, the rays deviated from the original path by the grain edges (fig. 4, screen 1), a part of the deviated rays (fig. 4, screen 2), or, finally, only the rays transmitted through the specimen without disturbing the geo-

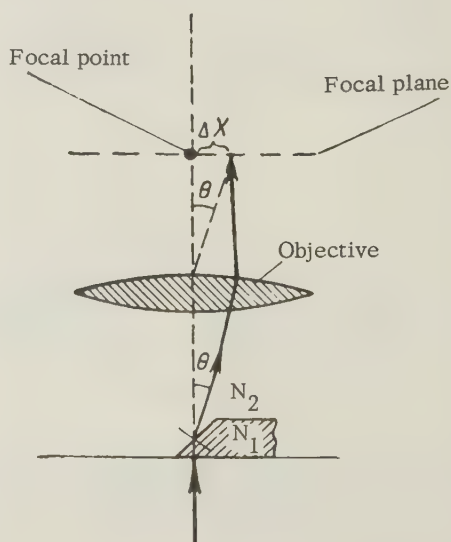


FIGURE 3. Linear deflection of the refracted ray at the rear focal plane of the objective.

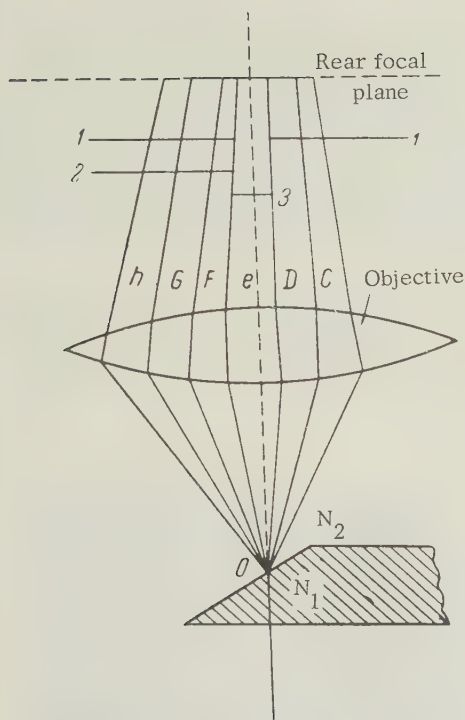


FIGURE 4. The spectrum formed by a white light ray in the rear focal plane of the objective. Indices of refraction of the two media coincide in the middle part of the spectrum.

metric course (fig. 4, screen 3), i.e., the rays with the linear dispersion equal or close to zero.

In all cases such screening will produce some effect on grains of the crystal under investigation in immersion liquid; this effect permits forming an idea of the relation between the indices of refraction of the two media. Depending on the procedures used, the first method has been called "apertural screening", [Koltzevoi--literally "circular" or "annular". In this translation the term "apertural" will be used instead as more descriptive.], the second method "unilateral screening", and the third "central screening". They are described separately below.

#### Apertural screening

It follows from formula (3) that the deviation of a ray from its original path depends both on the difference of the indices of refraction of the two media and on the angle of incidence of the ray at the refracting surface of the grain. It has been ascertained that refracting surfaces

in marginal sections of all the grains in the immersion preparation are almost vertical (80-85°). Therefore, grain edges represent those elements on which the deviation of rays may be essentially a function of the difference between the indices of refraction of the two media. For such a case formula (3) can be given as follows:

$$\Delta \theta = \frac{\Delta n}{N_{av}} K \quad (6)$$

where  $K = \tan 85^\circ$  -- a constant.

Formula (6) is, naturally, approximate, but it quite adequately reflects specific features of a narrow beam of rays passing through the marginal portions of the grains of the preparation.

Let us assume that the immersion preparation is illuminated by a beam of parallel rays from an illuminator or the sun. If the indices of refraction of the substance under investigation and of the liquid are not equal here, the rays of this beam at the grain edges will be deviated from the original direction at an angle determined by formula (6). Having passed through the objective of the microscope, the deviated rays will be collected at its back focal plane at a certain distance from the point in which the transmitted undeviated rays collect (Rays which pass through liquid and grain sections with small refraction angles will experience no noticeable deviation). As was shown above, this distance for the rays transmitted through the sections of the grain edges will depend only on the difference of the indices of refraction of the two media, as expressed by formula (7):

$$\Delta X = \frac{\Delta n}{N_{av}} K f$$

If a screen is placed in the focal plane of the objective in such a manner that it covers those points of the plane in which the rays deviated by the crystal edges converge, then with a given difference of the indices of refraction between crystal and liquid, these rays will not pass through the optic system of the microscope. In this case, the grain edges will appear dark. The remaining opening in the focal plane of the objective will let through only those rays which are not deviated from the original direction and the rays deviated by the parts of the object at angles which are smaller than those at its edges. Therefore, the grain sections nearer to the middle will be illuminated as much as the field. (The field is understood to be the portions of a preparation free of grains, i.e. filled with liquid only.)

When the indices of refraction of the two media are equal, the rays of illuminating beam will not experience deviation on the refracting surface of grains, and all will pass through the opening. In this case the grains will be uni-

formly illuminated without showing any dark edging. This, however, is true only under conditions when the preparation is illuminated in monochromatic light. In white light, when the indices of refraction of the two media coincide for some wavelength of the visible section of the spectrum, a colored border will be observed along the grain edges; the coloring of this edge will correspond to the wavelength for which the indices of refraction coincide, because the rays of other wave lengths will be deviated to one or another degree from the initial direction and be blocked by the screen (fig. 5).

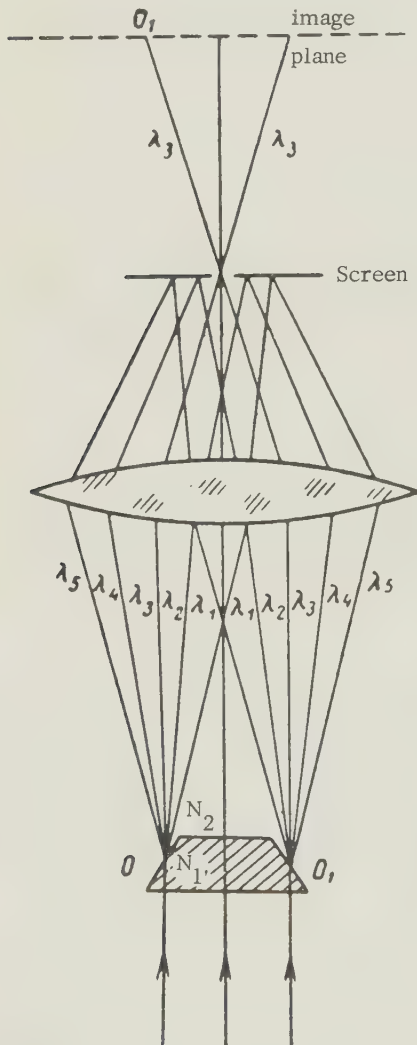


FIGURE 5. Development of the color effect in apertural screening.

Thus, apertural screening enables chromatic variation without using the monochromatic illumination.

The effect of the apertural screen is observed simultaneously on all the grains in the immer-

sion preparation in adjusting the focus. This type of screening may be used not only for more precise measurements of the index of refraction of the substance during investigations in white light, but also under the microscope for visual distinction of solid transparent phases of a similar index of refraction on the basis of their different dispersion coloring in the same liquid. The greater the dispersion difference of the two media, the better is the dispersion effect manifested.

In the practical application of the proposed method of comparison of the indices of refraction of the two media, the microscope objectives must be provided with iris-diaphragms in the back focal plane (fig. 6).

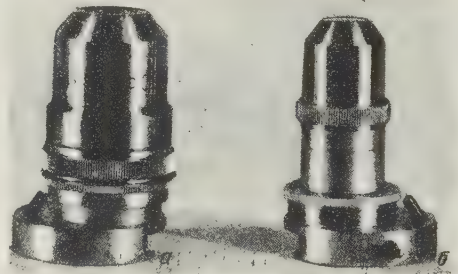


FIGURE 6. (Photo of) objectives with  $OC\phi-16\times$  (a) and  $OC\phi-22\times$  (b) iris-diaphragms manufactured by the OOMZ plant.

The iris-diaphragm in apertural screening must close down so that an opening about 0.5 mm in diameter may remain (objectives with iris diaphragms with 16x, 22x, and 40x enlargements are now manufactured by the OOMZ plant in Leningrad. Objectives with 16x enlargement are best). The quality of the image deteriorates very much when dimensions of openings are smaller. Thus, the permissible size of the opening limits somewhat the accuracy of measurements. Furthermore, it is practically impossible to obtain a definitely parallel bundle of rays; at best, the diversion of the ray directions is 2-3°. Considering this, the accuracy of measurements carried out by means of the proposed method is estimated to be 0.001-0.002.

In the practical application of apertural screening, the sets of dispersion liquids must be supplemented with tables of corrections for the dispersion of the indices of refraction of liquids for the optical center-of-gravity of all parts of the visible spectrum and with a chart of all their colors. The color chart is required for the correct definition of the visible coloring.



## Unilateral screening

The method described above is based upon the principle of symmetrical screening. By this method, the rays which are deviated by refracting surfaces of grains at equal angles to both sides of the original direction, are held back simultaneously. But in the unilateral unsymmetrical screening, depending on the screen position in the focal plane of the objective (fig. 7), only the rays which are deviated to one side at certain angles can be held back.

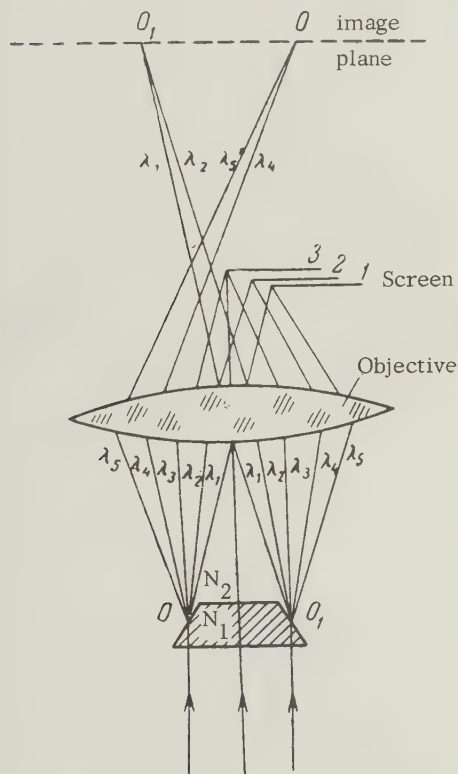


FIGURE 7. Development of the color effect in unilateral screening.

In contrast to apertural screening, the method of unilateral screening permits holding back the rays deviated from the original direction at a smaller angle, and, therefore, enables observation of the effect produced by the screening not only on the crystal edges, but also in portions away from the edges and having smaller refracting angles. To approach the same result in symmetrical screening it would be necessary to close down the iris-diaphragm of the objective and made the remaining opening smaller than permissible.

We shall describe the effects which are observed on the grains of a preparation when unilateral screening is used under various conditions.

When the indices of refraction of the two media are not equal and monochromatic illumination is used, the darkening of the grain on one side will be observed at a certain moment during the moving of the screen from the periphery to the center in the focal plane. During further shifting this darkening will extend to the parts away from the grain edges. The other part of the grain will remain illuminated. The field and the central parts of the grains will get darker in that case, because a part of the rays passing through the preparation without deviation will be held back (since in practice the width of the illuminating bundle does not equal zero). When the screen is advanced beyond the point of convergence of the rays passing through the preparation without deflection from the original direction, the field will become dark and a narrow band of light will be visible on one of the crystal edges.

If the indices of refraction of the two media are equal during such shifting of the screen, no uneven distribution of light will be observed on grains of the object under investigation, rather they will become extinguished evenly along with the field. Of course, the latter occurrence is true only in the case when monochromatic illumination is used. However, if the preparation is illuminated with white light, then under the same conditions a color effect will appear on the grains of the substance under investigation, manifested by different colors on different sides of the grain. This color effect will depend, first, on the spectral range in which the coincidence of the indices of refraction of the crystal and liquid takes place, and, secondly, on the position of the screen in the back focal plane of the objective. This is illustrated in Figure 7.

The changes in dispersion colors described above follow a pattern, and cannot cause confusion when forming an idea of the spectral range in which the indices of refraction of the two media coincide. On the contrary, such a change of colors can be used as an indicator. Table 2 shows two groups of colors. One group corresponds to the case of the "gray" field, when the screen does not completely close the angular opening created by the aperture of the illuminating bundle; the other group corresponds to the dark field when the screen covers it entirely. In the latter case the color observed on one side of the grain is formed by rays of wavelengths with index of refraction greater, and on the other side smaller, than that of the liquid (see fig. 7, 3rd position of the screen). In the gray field, each of these colors will contain the rays of wavelength for which the indices of refraction of the two media coincide (fig. 7, 2nd position of the screen).

The colors in pure crystals are very distinct; they are observed not only on the crystal edges but also in the larger area outward from

TABLE 2. Dispersion colors in unilateral screening

Spectral range of coincidence of indices of refraction	Color shades observed	
	Gray field	Dark field
Red	Dark-red and pale greenish azure	Darkness* and greenish azure
Yellow	Red and green	Red and azure-green
Green	Orange and dark azure	Orange-red and dark blue to azure
Azure	Canary-yellow and dark blue	Orange and dark blue-violet
Dark blue	Yellow and dark blue-violet	Yellow and violet
Violet	Pale yellow and dark violet	Pale yellow and darkness*

\* note: [Tiemnyi, literally "dark" (shade)].

the edges, which is very important in measuring the indices of refraction of small grains. The color effect is static in the sense that it is observed at one setting of the focus and simultaneously on all the grains in the field of vision.

In unilateral screening one needs an objective provided with an iris diaphragm, the same as for the preceding method. The iris diaphragm must be somewhat opened, and the illuminating bundle of rays must be directed at an angle to the optic axis of the objective. Shifting of the screen in the focal plane of the objective in this case will be accomplished during the closing of the iris diaphragm.

Because of its sensitivity and accuracy in measurements, the method of unilateral screening is better than the apertural method. The effect which is observed during unilateral screening does not differ from the one produced by the double diaphragm method, but the conditions of its appearance are more favorable. The accuracy of the measurements obtained by means of this method in monochromatic light can be estimated to be 0.0001-0.0002.

### Central screening

In contrast to the "apertural screening", in which the screen holds back the rays deviated from the original direction, the method of central screening, on the contrary, is intended to screen those rays that pass through the immersion preparation without deviating from the geometric course. It follows from the above that when the indices of refraction of a crystal and liquid are equal all the rays of the illuminating bundle, having passed the immersion preparation, will be held back by the screen, and the field therefore will not be illuminated. When the indices of refraction of the two media are not equal, the dark field will be invaded by the rays deviated by the refractive surfaces of the crystal. This invasion will be manifested by the appearance of a bright border along the crystal edges and by a brightening of the grains. The bright border on the grain edges is the Becke line, and, therefore, in defocusing the microscope, it will move as such. It is natural that in white light, a bright line will form on the edges of grains only when the indices of re-

fraction of the two media have not been made equal for any wavelength of the visible spectrum.

With the indices of refraction of the crystal and liquid coinciding, one or another color effect will be observed on grains of the substance being investigated, depending on the spectral range in which the coincidence takes place. In focusing the preparation, the coloring of the crystal edges will be complementary to that spectral range in which the coincidence was obtained (fig. 8). If the coincidence of the indices

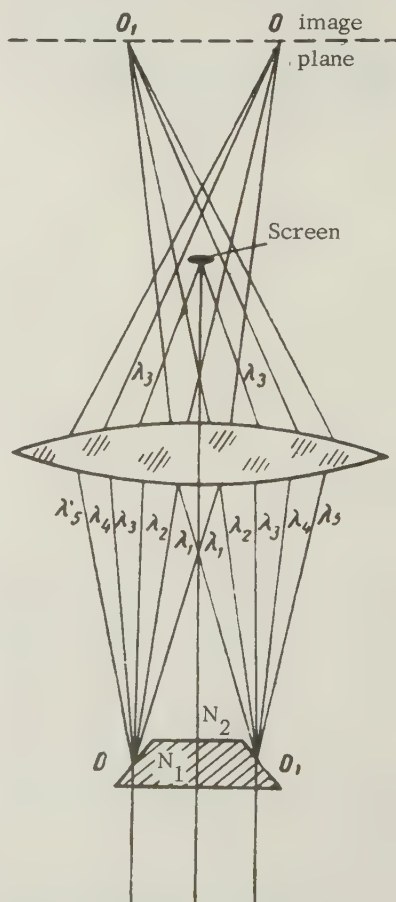


FIGURE 8. Development of the color effect in central screening.

of refraction is obtained near the ends of the visible spectrum, then the color effect will not change when the microscope is de-focused. In all other remaining cases, when defocusing the microscope, two colored lines will be observed moving in opposite directions. The color of one of these lines is caused by the rays with the index of refraction of the substance under investigation being greater, and of the other line smaller than the index of refraction of the liquid.

The colors observed in central screening are given in Table 3.

The central screening method, like those described above, provides chromatic variation in white light without the use of color filters.

In working in white light the values of indices of refraction obtained by the use of central screening are more accurate than those obtained by the Becke method.

# Directions for the application of apertural screening

## Setting up the illumination

Correct setting-up the illumination is one of

TABLE 3. Dispersion colors in central screening

Spectral range of coincidence of indices of refraction	Observed color shades of lines	
	in focusing	in defocusing
Red	Greenish azure	Greenish azure
Yellow	Color of diluted violet ink	Red and dark blue-azure
Green	Crimson	Orange-red and bluish violet
Azure	Diluted orange red	Orange and blue-violet
Dark blue	Diluted orange	Yellow and violet
Violet	Pale yellow	Pale yellow

Transitional colors of fringes are characteristic of intermediate spectral ranges not given in the table. They are quite conspicuous on the background of the dark field. In defocusing the character of moving colored fringes can be used in estimating the relation of the dispersion of the two media.

In order to apply central screening, one must place a dot screen in the back focal plane of the objective. The screen dimensions must be designed for the use of a narrow illuminating bundle of light. Since, in practice, it is difficult to obtain a width of the bundle smaller than  $2^\circ$ , then the latter determines the smallest size of the screen. The application of the illuminating bundle of the given width, of course, is possible only for objectives of small magnification. The width of the bundle for objectives of medium and large magnification must be somewhat increased.

The screen dimensions corresponding to an aperture of the illuminating bundle can be determined by formula (5) in which, in this case,  $\Delta X$  will designate the screen radius. And vice versa, knowing dimensions of the screen and the focal distance of the objective used, one can form an idea of the aperture of the bundle of rays used for illumination, and, therefore, of possible errors in measurements.

The screen is a plane-parallel plate made of well-polished, sufficiently thin and uniform (optical) glass with an opaque dot about 1 mm in diameter on it. This plate is placed in the upper focal plane of the objective so that the opaque screen lies approximately on the axis of the system (fig. 9).

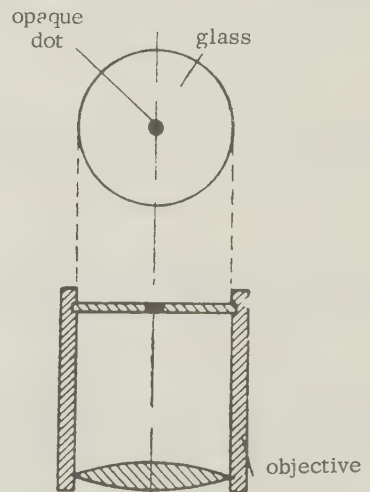


FIGURE 9. Schematic drawing showing installation of a dot-screen on the objective.

the most important requirements in the observation of the dispersion effect described above. As was said, the immersion preparation must be illuminated by a narrow bundle of rays. For this, first of all, the condenser lens of the microscope must be removed.

In all modern microscopes this is done very simply. Only illuminators of the OI-7 or OI-9 type provided with the iris diaphragm and capable of the required brightness of illumination are suitable. The light of such an illuminator, the diaphragm of which first is halfway closed, is directed to a plane mirror of the microscope and reflected by it to the objective.



Having removed the ocular or introduced the Bertrand lens, the illuminated point (the image of the source of light) in the focal plane of the objective is observed (fig. 10 a).

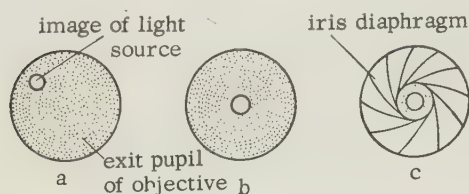


FIGURE 10. Schematic drawing showing installation of illumination in apertural screening.

The illuminated point is set approximately in the center of the exit pupil of the objective (fig. 10 b) with the aid of the mirror, and the iris diaphragm of the illuminator is closed almost wholly. By operating the diaphragm this way, the dimensions of the visible image of the light source decrease. Next, the iris diaphragm of the objective is closed as much as possible. If the image of the light source does not happen to coincide with the opening of the iris diaphragm, i.e., it is not in the center of the opening, then the image is moved to the center by a slight turn of the mirror.

It is mandatory that the image of the light source be always smaller than the aperture of the diaphragm closed as much as possible. This is accomplished by subsequent adjusting the diaphragm of the illuminator.

If all the rules described above for the installation of the illumination are followed, we shall observe a picture in the focal plane of the objective, as is shown in Figure 10 c.

The measuring of the index of refraction can be started only after an accurate setting of the illumination; otherwise, the necessary effect will not be obtained (rather an effect of unilateral screening will be seen).

#### Preparation of the mount

The immersion mount is prepared in the usual manner. It is necessary only to prevent tilting of the cover glass, which may happen with coarse grains in the mount, or with insufficient immersion liquid. This type of tilting will disrupt the setting of illumination during rotation of the stage, and consequently the effect itself. In the absence of tilting, however, the centering of illumination during the rotation of the microscope stage is not upset. When the mount is prepared properly, it is set on the microscope stage and measuring follows.

#### Measuring procedures

First of all we shall discuss the measuring

of the indices of refraction of isotropic minerals. A mount is set on the microscope stage and is first examined without the iris diaphragm in the objective. This step is necessary for adjusting sharp images. After obtaining the sharp image, the iris diaphragm of the objective is introduced and the effect on the grain edges is observed.

If the index of refraction of the mineral under investigation is considerably greater or smaller than that of the immersion liquid for all wavelengths of the visible spectrum, then one can observe dark, almost black, fringes on the edges of all grains. In order to establish which medium (liquid or mineral) has the greater index of refraction, the iris diaphragm is opened and the motion of the Becke line is observed; thus, the order of the required replacement of liquids (whether in direction of the increase or decrease of the indices of refraction) is determined.

Another mount is prepared, or the liquid in the first mount is changed, the index of refraction of the new liquid differing approximately by 0.03; the effect, which appears on the edges of the grains with the iris diaphragm of the objective closed down, is again observed. Similar changes of liquids must be continued until the coloring appears on the edges of the grains. By observing the character of this coloring and knowing the indices of refraction of the immersion liquids for different wavelengths, one can determine the index of refraction of the mineral in the spectral range in which the indices of refraction of the two media coincide.

Let us assume that during the apertural screening green fringes are observed on the edges of grains of an unknown isotropic mineral in the liquid of  $n_D = 1.500$ . By using the Table 2 attached to the standard set of immersion liquids which gives the magnitudes of dispersion of the liquids of the set, we find that the indices of refraction of this liquid and, therefore, of the mineral equal  $1.500 + 0.005 = 1.505$  in the green spectral range.

When color fringes corresponding to other spectral ranges are observed, the index of refraction of the mineral for these wavelengths is determined, applying corrections from the Table 2 of the set.

In order to determine the index of refraction of a mineral for the wavelength of sodium light from the indices of refraction obtained for various parts of the spectrum, a correction to the dispersion of the mineral must be introduced. It is determined experimentally. For this it suffices to determine the spectral ranges in two adjacent liquids, in which the indices of refraction of the mineral and liquid coincide, and then

to calculate for these spectral ranges the indices of refraction of the mineral by means of the method described above. The difference between these two indices of refraction will be the value of the index change of the mineral in the interval of these wavelengths. Comparing it with the value of the index change of the liquid in the same interval, corrections are made for the dispersion of the mineral in proportion to the ratio obtained. For instance, in a liquid with  $N_D = 1.600$ , the indices of refraction of the mineral and liquid coincide in the azure range of the spectrum, and in a liquid with  $N_D = 1.606$  in the yellow-green range. Hence, using the correction table, the indices of refraction of the mineral in the azure and yellow-green ranges are  $1.600 + 0.015 = 1.615$  and  $1.606 + 0.004 = 1.610$  respectively.

Therefore, the value of the change of the index of refraction of the mineral in the given interval of wavelengths is 0.005. The index of refraction of the liquid for the same interval changes by 0.011. The ratio,  $1/2$ , of the determined values can be accepted approximately as the ratio of the dispersions of the two media. In order to determine the correction to the dispersion of the mineral for whatever wavelength, the correction to the dispersion of the liquid for the same wavelength must be multiplied by the obtained ratio.

Thus, in order to calculate the index of refraction of the mineral for sodium light, the correction to the dispersion of mineral must be deducted from the corresponding correction of the liquid for the same spectral range, and this difference must be added to the index of refraction of the liquid used (for the wavelength of sodium light). In large-scale determinations, approximate corrections to the dispersion of the mineral can be used, accepting them equal half of the corresponding corrections of the liquid. Compared with the mean corrections to the dispersion of the mineral proposed by N. M. Melankholin, they will provide more accurate values.

In determining indices of refraction, the yellow, yellow-green, green or azure colors of fringes, which we shall call the critical determinative colors in further discussions, are best to use.

In using these fringe colors, the precision of measurements carried out by the described method attains 0.001 even during large-scale determinations, which makes it quite adequate for petrographers and mineralogists.

The utilization of the color effects of the extremes of the spectrum (red, blue, and violet) results in less precise measurements. These color effects, which we shall call "orienting" in our further

discussions, can be successfully used in the selection of liquids, because they permit estimating an approximate difference between the indices of refraction of the two media in the middle part of the spectrum, which is especially needed when working with minerals of high refraction. In that case, because of the high dispersion of liquids, the orienting effect can be observed at the difference of the indices of refraction of the two media equal to 0.030-0.040 for the wavelength of sodium light.

The study of anisotropic minerals becomes somewhat more involved because of the fact that their indices of refraction change within definite limits depending on the direction of light propagation in a crystal. The purpose of the measurement of the indices of refraction of anisotropic minerals is to determine these limits, to find the minimum ( $\alpha$ ) and maximum ( $\gamma$ ) values of the index of refraction.

It is accomplished as follows. An immersion preparation is prepared in the usual manner, and the effect produced on the screen is observed. If the values of the indices of refraction  $f$  from  $\alpha$  to  $\gamma$  of the mineral under investigation do not coincide with those of the liquid used for any wavelength of visible light, then dark fringes will be observed along the edges of all the grains in the immersion preparation.

Having mapped out the subsequent order of selecting liquids by means of the Becke method, a preparation containing a liquid with the index of refraction different by 0.030 is prepared, and the effect on the screen is observed again. If the liquids are being changed in the direction of increasing indices of refraction, then a blue-violet coloring (the "orienting" effect) will appear on the mineral grains in one of the sequence of preparations. If the change took place in the reverse direction, the coloring would be reddish-brown. Following the appearance of the orienting effect, the next preparation is made with a liquid differing from the preceding one by a smaller value of the index of refraction (0.010-0.020). The similar change of liquids continues until the colors on the grain edges of the mineral under investigation become critical.

Obviously, the critical colors of the anisotropic mineral will be different on different cross-sections characterized by different indices of refraction. The minimum index of refraction is recognized by the critical color which is the smallest (The increase in coloring is considered to proceed from the red to the violet part of the spectrum.) of all those observed in the preparation. No coloring of borders below the critical colors (red) should be observed here.

In contrast to the minimum index of refraction, the recognition of the maximum index is based on the critical color shade (which is)



highest of all those observed in the preparation. No color shades should show above the critical shades (blue or violet). If the birefringence of the mineral is considerable, then the color shades may show outside the critical shades. In such cases, the minimum and maximum indices of refraction are determined each on a separate preparation following the instructions given above.

In determining the intermediate principal index of biaxial minerals, the sections are selected so that the colors on the edges of grains do not change during their rotating; or, using the statistical method, the minimum value of  $\gamma'$  or maximum value of  $\alpha'$  is determined (while watching the change of colors of fringes on different grains during rotation of the microscope stage).

Let us show it in an example. Assume that, by using this method, the intervals of the change of coloring of fringes on individual grains were established as follows: (a) yellow ( $\alpha'$ )--dark blue ( $\gamma'$ ); (b) green ( $\alpha'$ )-- azure ( $\gamma'$ ); (c) azure ( $\alpha'$ )--dark blue ( $\gamma'$ ).

In this case the maximum value of  $\alpha'$  has a corresponding azure fringe. The similar effect corresponds to the minimum value of  $\gamma'$ . Since  $\alpha'$  cannot be greater, nor  $\gamma'$  smaller than  $\beta$ , the latter is determined by calculating the maximum value  $\alpha'$  or minimum value  $\gamma'$ , from their established color effects.

Observation of the color effect in apertural screening provides an opportunity to determine the principal indices of refraction of minerals by means of the statistical method with the same accuracy as by means of the theodolite method. Exceptions to this are minerals with the perfect cleavage, such as micaceous one. The use of the color effects facilitates finding grains needed for determining the principal indices of refraction, which is especially important in the study of minerals of high birefringence.

Possible applications of the statistical immersion method are widened through the observation of the color effects, because, in determining the principal indices of refraction of anisotropic minerals, it permits using the sections of the indicatrix, such as  $\alpha\beta$  and  $\gamma\beta$ , which usually are not used with the Becke method. As is known, in applying the Becke method, the sections of the indicatrix generally utilized for this purpose are closer to  $\alpha\gamma$  and are characterized by the highest interference colors with crossed nicols.

The color effect is retained during a rotation of the mineral section 30-40° from the position of extinction; thanks to this, with a great number of grains in the preparation (thus guaranteeing their most varied orientation), the turning of

the microscope stage becomes unnecessary. When only a few grains are observed in the field of vision of the microscope, it is necessary to turn the microscope stage at least 90° in the course of observations.

In order to obtain a higher accuracy of measurements in apertural screening, the periodical checking of the indices of refraction of the immersion liquids is necessary.

#### Directions for the application of unilateral screening

As was already mentioned, an iris diaphragm objective can be used to obtain the effect of the unilateral screening. Accordingly, practical directions are given below.

#### Setting up the illumination

As in apertural screening, setting up of the illumination is accomplished with the aid of the Bertrand lens or with the ocular removed. Having set the diaphragm in the illuminator as in the preceding method, the image of the source of light, visible in the upper focal plane of the objective, is set with the aid of a plane mirror nearer the western or eastern edge of the objective exit opening (fig. 11a). The iris diaphragm of the

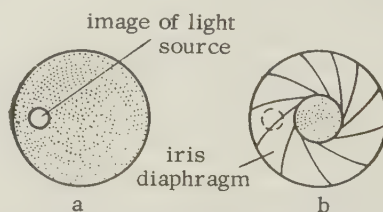


FIGURE 11. Schematic drawing showing installation of illumination in unilateral screening.

objective in this case must be opened. If the image of light is not sufficiently bright, then its maximum brightness is achieved with the aid of the illuminator, leaving the mirror alone.

The installation of illumination is checked by the closing the iris diaphragm as much as possible: if the installation was carried out properly, then the image of the source of light would be behind the screen (fig. 11b); if, however, the image was not offset far enough from the center of the objective exit, then it would not be fully masked by the screen. In the latter case the complete extinction of the field of vision of the microscope cannot be attained with the aid of the iris diaphragm and, therefore, it is impossible to observe the second group of colors (see table 2).

In order to be able to compare the indices of refraction of the two media quickly, it is necessary to follow a definite plan in setting up the



illumination, i. e., to set the image of the source of light always in the upper focal plane of the objective in a particular position, either on the right or the left of the center of the objective exit. The reasonableness of this recommendation can be seen from the following.

When using a special objective equipped with the iris diaphragm, the position of the image of the light source determines also the position of the screen. Moreover, if observations of the image of the light source are carried out with the aid of the Bertrand lens, the position of the screen will be opposite to the position of the image; and without the Bertrand lens (with the ocular removed), the positions of the screen and of the image of the light source will coincide.

Knowing the position of the screen and watching the distribution of light and darkness on the grains of the immersion preparation, one can determine which of the two media has a greater index of refraction. It is easy to see from figure 7 that when the index of refraction of a mineral is greater than that of the liquid, the extinction of the crystal in the screening process will begin at the side of the grain opposite to the screen. But because the microscope gives a reverse image, the extinction of the grain will be observed on the side facing the screen. If the index of refraction of the grain is smaller than that of the liquid, the effect will be opposite. To avoid having to relate the observed effect to the position of the screen every time, it is best to follow an established pattern of the installation of illumination.

In following the rules given above, or a practical course with respect to an accepted installation scheme, the distribution of light on the grains of a preparation should be determined for one or another ratio of the indices of refraction of the two media. When the difference between the indices of refraction is considerable, this will permit comparing the indices of refraction of the two media reliably and without loss of time until the color effect has been attained.

In judging the magnitude of the indices of the indices of refraction when the color effect is reached, only the combination of colors and not their distribution on a grain is important. The distribution of colors is important only in estimating the nature of the dispersion of the substance being investigated. Thus, if the dispersion of the mineral is greater than the dispersion of the liquid, the distribution of colors on the grain will be reverse to the one which takes place in the majority of cases during the study of minerals. The scheme of color distribution on the grain becomes pertinent only when working with solid organic substances.

measuring of the indices of refraction can be begun.

#### Measuring procedures

The immersion preparation is placed on the microscope stage and the screening effect is observed during gradual closing of the iris diaphragm of the objective. If the indices of refraction of the two media are not equal for any of the wavelengths of visible light, then we shall observe uneven distribution of light on the grains of the mineral. Depending on which side of the grain shows extinction, the medium with a greater index of refraction can be determined from the accepted scheme. Next, the liquids are selected in the order of the approach of their index of refraction to that of the mineral until the color effect has been observed. In checking each new preparation the iris diaphragm of the objective is first opened, and then smoothly closed. This order must be followed particularly during the appearance of the color effect to make possible the observations of both groups of shades given in Table 2.

Having obtained the coloration, the spectral range in which the indices of refraction coincide is determined with the aid of Table 2. Subsequent steps in the procedure will be similar to those in apertural screening. For an isotropic object, the coloration (the combination of colors) will be identical on all the grains of the immersion preparation, and for an anisotropic substance, different combinations of colors will be observed on different grains.

If changing the liquids was carried out in direction of the increasing indices of refraction, then the minimum index of refraction of the mineral would be determined in that liquid which shows the coloring first. The principle of the method of apertural screening for determining the lowest color shade observed is also applicable to this case. As is seen in Table 2, the lowest or highest shade is a combination of colors corresponding to the coincidence of the indices of refraction of the two media in the red or violet range of the spectrum respectively. By using this scale and observing combinations of colors on different grains of the anisotropic substance under investigation, it is easy to determine the lowest of the shades under observation.

A similar procedure is used in determining the maximum index of refraction of the mineral, this time observing the highest of the color shades. Using the same table, the spectral ranges corresponding to these lowest and highest shades are determined and the corrections to the index of refraction of the liquid in the preparation are introduced as shown above (see "Directions for the application of apertural screening").

Illumination arrangements completed, the

At first the investigator will have to use

Table 2 to evaluate shades and establish corresponding spectral ranges, but after some practice this evaluation will be done quickly and correctly without the table.

The interpretation of the dispersion effect during unilateral screening differs essentially from that in apertural screening by an additional operation: the two-color shades observed here are reduced to those which are observed in apertural screening directly. It follows that what was said about measuring the indices of refraction by means of the previous method is also true for this method.

In conclusion, it is necessary to consider the characteristics of the gray and dark fields for which the shades are given in the table.

If the illumination was set up properly, then the brightness of the field of the microscope decreases progressively during the gradual closing of the iris diaphragm of the objective, and at a certain moment the field of vision becomes intermediate between light and dark. Such a field will be called "gray". If the iris diaphragm is closed still more, the field of vision of the microscope becomes entirely dark, almost black. This field will be called "dark".

The effect of the unilateral screening is best observed in the gray field. In this case, the dispersion coloring observed along the entire area of the grain is most distinct. The color effect in the dark field is observed only on the grain edges, and the grains are not plainly visible in the dark background.

Observations in the "dark" field are recommended only for controlling the accuracy of evaluation of color shades in the gray field and only in doubtful cases. The change of dispersion colors in different spectral ranges of coincidence of the indices of refraction of the two media is quite orderly; therefore, it is not difficult to determine possible color combinations for the spectral ranges not given in the table, for instance, for such as orange, yellow-green, and green-azure. The color shades observed for these spectral ranges will be intermediate between the two colors adjacent. Thus, for instance, when the indices of refraction of the two media coincide in the yellow-green range of the spectrum, the combination of orange-red and azure tinges in the gray field and of deep orange-red and azure in the dark field will be observed on grains of the substance being investigated. Color shades possible in other intermediate ranges of the spectrum can be established similarly.

Known minerals are best for studying the dispersion colors. The accuracy of the evaluation of a color shade may be first verified by means of apertural screening. Thus, if a combination of the orange (one one side of the

grain) and azure (on the other) has been observed on grains in the gray field, then a green border must show around the grain in case of apertural screening. This type of checking becomes unnecessary when experience is acquired. But sometimes even an experienced worker, especially in doubtful cases, finds this checking helpful in attaining greater accuracy of measurements.

The combined application of unilateral and apertural screenings permits checking 100 percent of the grains of an immersion preparation. The former method yields a better effect on refracting surfaces oblique to the microscope axis, and the latter on surfaces nearly vertical. As a rule, either surface may occur in an immersion preparation but not always on the same grain. Unilateral screening enables observation of the dispersion effect on smaller grains, which is its advantage over the first method.

#### Directions for the application of central screening

As was said above, in observing the effect of the central screening it is necessary to install a dot screen in the upper focal plane of the objective to be used in the investigation. Inasmuch as the upper focal plane of 3.7x and 8x objectives is accessible to the observer, and as the screen required in the procedures can be handmade, some practical advice for the preparation and installation of the screen is given below.

#### Setting up the illumination

A screen can be made quickly and simply on a cover glass. The latter can be conveniently and easily cut to furnish a plate of the required dimensions. However, such a screen is brittle and will not last long. Therefore, a screen prepared on a glass thicker than cover glass will be more practicable.

The dimensions of the plate holding the screen must be such that it can be set in the upper plane of the 8x objective case or in the free opening of the plate of an analyzer (for the 3.7x objective). By using India ink or any other nontransparent material, an opaque dot about 1 mm in diameter is marked in the center of this plate. The plate with its dot screen is set in such a manner that the screen may be found approximately in the center of the objective exit. The accuracy of the installation is controlled by a Bertrand lens or by the removal of the microscope ocular. Having set the screen, the image of the source of light visible in the focal plane is brought into line with the screen so that it may be placed symmetrically with respect to the screen (fig. 12 a).

If the diaphragm masks the illuminator very much, and the dimensions of the visible image



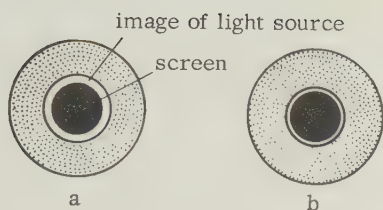


FIGURE 12. Schematic drawing showing installation of illumination in central screening.

of the source of light are smaller than of the screen, then the iris diaphragm should be opened. But when the required position of the image of the light source is attained, the diaphragm is closed again so that the dimensions of the image and screen become nearly equal (fig. 12b).

By removing the Bertrand lens or by inserting the ocular in place, the field of vision of the microscope is observed. It must be dark-gray. If it happens to be entirely dark or almost black, the iris diaphragm of the illuminator should be opened somewhat until the field of vision becomes slightly brightened.

The measurement of the indices of refraction can be started after completion of the installation.

#### Measuring procedures

At the stage when the indices of refraction of the two media still differ considerably from one another, i. e., when they do not coincide for any one of the wavelengths of visible light, the Becke line is used. In a given case it is expressed more clearly as it is observed under more favorable conditions (dark field). In case of the occurrence of color shades, Table 3 is used.

Because the rules for calculating the index of refraction with the use of shades observed do not substantially differ from those used in interpreting the dispersion effect of unilateral screening, we shall not discuss this matter here.

#### Determination of the indices of refraction of minerals containing inclusions of other crystals or occurring in intergrowths

The dispersion effect observed on the grains of an immersion preparation during focal screening enables effective solution of the most difficult problems arising when the Becke line is used. Thus, for instance, if a mineral grain has many fine inclusions of another mineral or if a mineral under investigation appears in the form of very thin growths with another mineral, then the Becke line that appears on the grains may be masked with a line appearing in the area of the grains of inclusions. In consequence, the

total effect becomes so illegible that it may lead to a distortion of the measurements. A color effect helps to distinguish the main mineral from admixtures either by the character of the coloring of one of the minerals or by the absence of color shades in one of them.

Let us assume that the powder to be investigated is represented by intergrowths of potash feldspar and quartz. Then in a liquid with the index of refraction close to that of potash feldspar ( $N_D = 1.525$ ) the color effects which we obtain on grains (or grain sections) of the feldspar and quartz will be different. Owing to this, it is possible by selecting a liquid in a proper manner to determine correctly the indices of refraction of each mineral in intergrowths. Of course, this can be accomplished successfully only when the indices of these minerals do not overlap one another and when there is some break between the maximum index of one and the minimum index of the other mineral.

The accuracy of determining the indices of refraction of border and central parts of zoned plagioclases becomes greater with the color effect.

#### Determination of elements of the optical indicatrix by the dispersion effect

In many instances, an idea of the axial nature, [that is, whether the mineral is optically uniaxial or biaxial], optical character, and other elements of the optic indicatrix of the mineral in question can be formed simultaneously from the dispersion effect observed during measurement of the indices of refraction.

Indeed, one or another color shade appearing on the grains of an immersion preparation in a given liquid corresponds to a definite value of the index of refraction. If the value of the index does not depend on the direction of propagation of light in the crystal, the mineral being isotropic, then the color effects observed on all the grains of such a mineral will be identical and will not vary during the rotation of the microscope stage. Almost the same effect will be observed for a very low (on the order of 0.003) birefringence of the mineral. In this case the change of color shades will be too insignificant to be easily recognized, especially in the interval 1.600-1.800 of the indices of refraction, and the anisotropic mineral can be easily mistaken for isotropic. Therefore, one ought to be very careful in judging that the mineral under investigation is isotropic on the basis of the effect indicated.

In most cases the dispersion effect makes possible the distinction between the uniaxial and biaxial minerals. Because any cross section of uniaxial minerals exhibits the ordinary index of refraction  $N_0$  (the constant value of the



index at one of the extinction positions), such minerals will be characterized by the same color shade at one of the positions of extinction of each grain. Quartz can be given as an example. The ordinary index of refraction of quartz in a liquid with  $N_D = 1.540$  of the standard set of liquids coincides with the index of refraction of this liquid in the green range of the spectrum. When the apertural screening is used, green borders will be observed along the edges of all the grains at one of the positions of extinction (during rotation of the microscope stage). At another position of extinction the border color on different grains may be any shade from green to blue-violet, as the amount of the index of refraction for these positions may be anywhere in the range from 1.544 to 1.553.

The optical character of the mineral is determined in relation to whether the permanency of a color shade corresponds to  $\alpha$  or  $\gamma$  of the mineral. If the shade lasts for  $\alpha$ , the mineral is positive optically, or vice versa.

The color effect characteristic of uniaxial minerals makes their identification in a mixture easier if their indices of refraction are similar. Such a case, for instance, may be encountered in the study of carbonates. If the carbonate under investigation does not contain admixtures, then a definite color effect corresponding to the value  $N_0$  of this carbonate will be observed on all the grains of the preparation (at one of the positions of extinction). The grains which do not register the same color effect will belong to admixtures. Thus it is possible to distinguish carbonates that differ in the value of the ordinary index of refraction by 0.003.

In order to make certain that the mineral is biaxial, it suffices to find two grains showing a different change of color shades. Thus, if during the rotation of the microscope stage, a change of shades from red to violet was observed on one grain and from green to azure on another grain of the same mineral, then we have the right to call the mineral biaxial. The latter must be obvious from the theory of the optical indicatrix of biaxial crystals.

The optical character of biaxial minerals can be established from the intervals of color changes on different grains during the rotation of the stage. The shortest intervals of the color changes will be observed in the range of higher color shades (for a given liquid) if the intermediate index of refraction  $\beta$  is nearer the maximum principal index, and in the range of low shades if the intermediate index of refraction of the mineral is nearer its minimum principal index. Appraisal of the shade intervals must begin with a liquid in which the minimum principal index of refraction was measured.

Let us illustrate it with an example. Assume that color shades resulted from coincidence of the indices of refraction of the two media in all spectral ranges from red to violet are observed on different grains in some liquid. If during the rotation of the stage the blue shade changed to violet on some of the grains, it would mean that the intermediate index of refraction of the mineral was near its maximum value. If, however, the change of shades observed were from red to yellow-green, then it would be possible to conclude that it is near its minimum value. It should be also obvious from the theory of the optical indicatrix of biaxial crystals that  $\gamma'$  cannot be less nor  $\alpha'$  greater than  $\beta$  of the mineral. In the first instance a change of the blue shade to violet indicates that we are dealing with a section  $\alpha' \gamma'$  in which the value  $\alpha'$  is near its maximum, since no higher color shade for  $\alpha'$  has been observed. In the second case, the shade change from red to green convinces us that we are dealing with a section  $\alpha' \gamma'$  in which the value  $\gamma'$  is minimum since no shades lower than green has been detected for  $\gamma'$ .

This method of determination of the minimum value of  $\gamma'$  or maximum value of  $\alpha'$  through the varying shades can be successfully applied to exact measuring of the intermediate principal index of refraction of a mineral. And the optical character of the mineral can be ascertained if the value of the intermediate index of refraction is known.

The determination of the optical character of a mineral by means of the method described above becomes difficult when the value of the intermediate index of refraction occurs in the middle between the minimum and maximum principal indices of refraction or in the case of a mineral of low birefringence.

#### Application of the dispersion coloration to quantitative mineralogic analysis

It is very difficult to establish the quantitative ratios of minerals when two or more transparent minerals with similar indices of refraction occur in a mixture and are hard to distinguish under microscope (by color, shape, or other characteristics). This difficulty increases when one deals with very fine powders or mineral intergrowths. Sometimes, in order to make the problem easier, some chemical stains are used to color one or another mineral, but at present this method has been applied to only a small number of minerals; besides, it requires too much time in preparation of material. A dispersion coloration of minerals, which becomes feasible with the method of "focal screening", presents considerably better possibilities to the researcher. In this case a set of immersion liquids can be considered as a collection of physical stains which can be applied to any coloring of the mineral in our investigation or

of several minerals in mixture.

The application of dispersion coloration is most convenient in those cases when the indices of refraction of the minerals in mixture are close to but do not overlap one another, in other words, when the maximum index of refraction of one mineral (anisotropic) differs from the minimum index of refraction of another mineral by at least 0.003. Another desirable property of the minerals in mixture is a moderate birefringence. If it is strong, the coloration of all the grains will not be possible, because, being close to their minimum or maximum value, the indices of refraction of such a mineral may turn out to be beyond the range of values of the indices of a corresponding liquid for all the wavelengths of visible light.

Thus, if the mixture of minerals meets the requirements, then the minerals can be successfully distinguished by their different dispersion colorations in one liquid.

In each individual case a liquid stain is selected on the basis of the ratio of the indices of refraction of the minerals in mixture, and the requirements of the problem. However, certain recommendations to be followed in the majority of cases can be given.

In order to distinguish two anisotropic minerals, it would be best of all to have a liquid with an index of refraction somewhat higher (by 0.002-0.003) than the maximum index of refraction of the mineral, the indices of refraction of which are generally lower than of the other mineral. Moreover, a color shade effected by the wavelengths of the spectral red range will always be observed on grains of the first mineral (with a lower index of refraction). The color effect caused by different ranges of the spectrum (except red) may be observed on grains of the other mineral, depending on the magnitude of the birefringence of the mineral and on the difference between the index of refraction of the liquid used and the minimum index of refraction of this mineral.

In order to obtain different colorations of potash feldspar ( $\alpha = 1.519$ ,  $\gamma = 1.526$ ) and quartz ( $\alpha = 1.544$ ,  $\gamma = 1.553$ ) in mixture a liquid with an index of refraction 1.528 will be best. In this liquid the dispersion effect observed on the grains of potash feldspar is caused by rays with the wavelengths in the red range, and on the grains of quartz in the violet range of the spectrum. It is obvious that such a coloration will take place because the coincidence of all the values of the indices of refraction ( $\alpha$  to  $\gamma$ ) of given minerals in a given liquid will occur only in these ranges of the spectrum. If albite ( $\alpha = 1.529$ ,  $\gamma = 1.539$ ) occurs in the same mixture, then the color bands observed on its grains will be in the range of yellow-green to blue. Thus, one can estimate the amount of each min-

eral in a mixture quickly and accurately applying the colorations described here. All other methods leading to determination of these three minerals and their content are more difficult and less accurate.

Similarly, any transparent minerals having similar ratios of indices of refraction and values of birefringence can be distinguished by different colorations in corresponding liquids.

By applying the dispersion coloration and the effect of screening that takes place when differences between the indices of refraction are considerable, it is possible to distinguish as many as five minerals with unilateral and central screenings, and as many as four with apertural screening. The method of central screening is more convenient in the quantitative mineralogic analysis as it permits working in the dark field; then the image of grains in the field is sharpest and the dark background does not tire the investigator. Furthermore, central screening affords an opportunity to work with finely dispersed material.

The dispersion coloration can be successfully applied to controlling the process of concentration, especially in a case of fine fractions, as well as in many other cases.

## CONCLUSION

When working in white light, the determination of the moment of coincidence of the indices of refraction of two media and the determination of that wavelength or, rather, the spectral range in which this coincidence takes place, become possible through the application of focal screening of an illuminating bundle of rays passing through the immersion preparation. The coincidence of the indices of refraction is established from the appearance of the color effect (dispersion effect), and the spectral range in which the coincidence occurred is established by the character of this color effect. In the case of apertural screening, the spectral range in which the indices of refraction of the two media coincide, is observed directly; in the unilateral and central screenings it is inferred from indirect indications.

Thus, the realization of a chromatic variation becomes possible in white light without turning to monochromatic illumination. Such a possibility permits, first, to bring the accuracy of measurements obtained in large-scale determinations up to the level of the so-called "reliable" measurements; and, second, it considerably shortens the time to be applied to the procedures of these measurements.

The dispersion effect observed in one or another screening procedure is stationary in the sense that no shifting of the microscope



drawtube is necessary during observation. This reduces the wear of the outfit, and does not tire the researcher's eyes as much as happens with the movable Becke line. Furthermore, the effect of screening is observed simultaneously on all the grains of a preparation that are in the field of vision, thus permitting the researcher to determine quickly the principal indices of refraction of an anisotropic mineral. Consequently, this method does not require the cumbersome statistical operations of the Becke method.

Analysis of the color effect that is observed on different grains of a preparation provides a more accurate and rapid determination of indices of refraction; in many instances it also permits solving many other crystallo-optical problems, such as determination of the axial properties [whether the mineral is optically uniaxial or biaxial] and optical character of the mineral being investigated.

The dispersion coloration can be successfully used under the microscope in the visual separation of the minerals in mixture with similar indices of refraction. This method has greater possibilities and advantages over the chemical staining procedures being used at present with the same purpose in view.

The focal screening can be accomplished by use of objectives of any magnification, but objectives of small magnification produce the best results; the latter should be used if the grain size of the mineral to be investigated has not been defined by nature itself, such as in the case of clayey minerals.

In the application of apertural and unilateral screenings the available objectives must be equipped with iris diaphragms in their rear focal plane. This design change of objectives can be accomplished without impairing their optical properties, and it does not present any difficulty for the optical instrument industry. Necessary accessories in the application of central screening can be made with one's own facilities.

In the practical utilization of the dispersion effect of focal screening, the sets of immersion liquids must be provided with tables of dispersions for the optical centers-of-gravity of all the sections of the visible spectrum and with a table of all the colors of these gravitational centers. The latter table is necessary for the correct estimating of the color shade being observed.

The digest presented above convinces us that the use of the Becke line in comparing the indices of refraction of the two media in white light must be limited to situations in which the difference between the indices of the two media is considerable. In other words, it can be used

only during the first stage (before the appearance of the color effect) as an orienting factor in the determination of the direction to be taken in changing liquids.

The devices which are required in addition to the available equipment (objectives) are simple. In comparison with all other methods, focal screening has many advantages for the investigator and presents possibilities of application of the dispersion effect to solution of other problems. All this raises hope that the proposed method of "focal screening" will become a common practice in mineralogic-petrographic laboratories.

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\*Ed.: No specific citations of these references are found in the text (except to Melankholin page 195).

# GEOCHEMICAL PROSPECTING FOR POLYMETALLIC ORE DEPOSITS IN THE EASTERN TRANSBAIKAL BY MEANS OF THE MUDS AND WATERS OF THE DRAINAGE SYSTEM<sup>1</sup>

by

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• translated by William Mandel •

## ABSTRACT

In 1956, the All-Union Scientific Research Institute for Prospecting Methods and Equipment (VITR) and the Chita Geological Bureau conducted joint studies to develop a prospecting method for polymetallic ore occurrences using muds and waters of the regional drainage system in eastern Transbaikal. The region is dry with distinctly continental climate; precipitation, averaging 330 millimeters per year, is proportionately heavier during the summer season. The Nerchinsky Zavod district, selected for study, is hilly with absolute elevations of 600-850 meters, cut into ridges by northeast-southwest trending ravines; and, characterized by a mature drainage system. Permafrost islands are widespread and vegetation is transitional between steppe and taiga types. Lower Paleozoic, Silurian, and Lower and Middle Jurassic sedimentary rocks occur to the west along with granite bodies and other intrusives. To the east, Lower Cretaceous sediments are extensive; Tertiary and Quaternary effusive appear and Proterozoic and lower Paleozoic metamorphic rocks are exposed over an extensive area along the Serebyanka River. Most ore occurrences are to the west in upper and lower Paleozoic, principally carbonate, rocks. Galena, sphalerite and pyrites occur in carbonates and some quartz, as lenses, veins, and irregular bodies. Limonite is predominant among oxidized ores, which include manganese oxides. Pb, Zn, Ag, As, and Sn, content is high; Sb and Cd are present. The following conclusions have been developed from preliminary work: Dispersion halos in stream-bed muds reflected occurrence and composition of polymetallic ore deposits on the sides of ravines. Small and medium-sized deposits were found to have halo heads as long as 4.5 kilometers and trains as long as 2.5 kilometers; according to the degree of sensitivity obtained by analysis. It was concluded that simultaneous determination for several elements is desirable, as well as sampling in two stages to reduce work volume: i.e., general sampling at 200-meter intervals to establish presence of ore bearing valleys; and 50-100-meter interval sampling to discover halos for individual deposits. Polymetallic deposits are identifiable by high  $\Sigma M$  (sum of metals present), or, essentially, the zinc content because of its widespread dissemination in natural waters in underground and surface waters. No false  $\Sigma M$  anomalies, not related to ore deposits, were encountered. Sampling of alluvium and talus waters and of country rock waters yielded identical results. It was established that hydrochemical prospecting should be during rainy periods when many springs appear in alluvium and talus; however, frequent and brief precipitation may complicate sampling results. Possible contamination of samples must be avoided, especially in sampling surface waters. Thus, hydrochemical prospecting for polymetallic ore deposits by sampling stream-bed muds proved to be particularly adapted to the regional conditions of eastern Transbaikal. A comparatively small number of samples is needed to find ore-bearing districts; probably one-tenth that required for areal metallometric survey of eluvium and talus on the usual 1:50,000 scale. In addition, muds of underground and surficial waters may reflect blind deposits not identifiable by metallometric surveys of talus. Heavy or extensive equipment, power source, or fuel haulage are not required; thus, analyses can be run by most field parties. Analysis methods have been developed for only a small number of elements, it is planned to develop these methods for use under a wider range of environments, and for use of indicators for a large variety of metal complexes. --D.D. Fisher.

\* \* \*

Ores in polymetallic deposits are unstable in the oxidation zone at the surface of the earth, and are readily subject to chemical decomposition or mechanical disintegration. The ore elements are transferred to waters washing the ore bodies and to their dispersion halos. As a consequence, the chemical elements characteristic of polymetallic ores necessarily have the tendency, upon their transport by surface streams, to accumulate in the fine mud-clay fraction of alluvial and, in particular, stream deposits. This phenomenon may be utilized for prospect-

ing. The so-called bottom sediment method, based on the existence of dispersion halos in drainage-system muds is currently employed only in uranium prospecting [5]. Dispersion halos in stream-bed mud-clay deposits have not been studied in terms of other formations, such as those of polymetallic ores. This method offers very good possibilities, however, in that it permits utilization of spectrometallometric surveys for areas covered with alluvium. Moreover, in such places the method represents a splendid supplement to gravity separation of unconsolidated materials because it supplements data provided by the latter where occurrences of minerals unstable under surface conditions are concerned.

<sup>1</sup>Translated from *Geokhimicheskkiye poiski mestorozhdeniy polymetallov v vostochnom Zabaykalye po ilam gidroceti i vodam: Novoye v Metodike i Tekhniki Geologorazvedochnykh Rabot*, Sbornik 1, Leningrad, 1958, p. 46-73.

The dispersion halos forming in surface and subsurface waters around polymetallic-ore formations are broadly utilized in hydrochemical

prospecting. However, the formation conditions of aqueous dispersion halos, and therefore the possibilities of conditions for carrying out hydrochemical prospecting vary in accordance with geologic, hydrogeologic, climatic, and other special features of the locality. Thus, it is necessary to check out the hydrochemical method as applied to a variety of geologic circumstances, and conditions of physical geography.

In 1956, the All-Union Scientific Research Institute for Prospecting Methods and Equipment (VITR) and the Chita Geological Bureau conducted joint studies in Eastern Transbaikalia for the purpose of developing a prospecting method for complex polymetallic ore formations using muds and waters of the drainage system; and, to determine the possibilities offered by this method, its dependability and place in the overall undertaking for prospecting under conditions in Transbaikalia. The conclusions derived are of general interest: This article sets forth in brief the results of work primarily in the vicinity of Nerchinsky Zavod.

M. A. Lapp, I. V. Lebedeva, N. V. Nikulnikov and D. A. Saar, in addition to the present authors, participated in these studies. Spectroscopic analysis of the specimens was done by A. A. Utgof, L. I. Bagurina and N. D. Dobrynya; and chemical analyses, by I. P. Mulikovskaya, S. L. Dobychin, Z. A. Vasilyeva and N. P. Nadezhkina. The work in the Aleksandrovsky Zavod-to-Akatuy district was done by L. F. Cherbyanova, with the assistance of V. A. Yefremov.

#### PHYSICAL GEOGRAPHY AND GEOLOGICAL STRUCTURE OF THE DISTRICT CONTAINING THE NERCHINSKY ZAVOD GROUP OF POLYMETALLIC-ORE DEPOSITS

The Nerchinsky Zavod group of occurrences lies in the northeastern part of the polymetallic ore belt of Eastern Transbaikalia extending along the left bank of the Argun River.

The relief is hilly, the absolute altitudes of up to 600-850 m. A series of valleys (ravines) cuts the district into a number of low ridges extending NE-SW. The ridges rise 100 to 150, or sometimes to 200 m above the valleys. The topography is gentle, with occasional projecting cliffs. The district is characterized by a sharply continental, dry climate. Precipitation, occurring chiefly during the summer, averages about 350 mm per year. Islands of permafrost are widespread. The district is in the transition zone between taiga and steppe vegetation.

The western portion of the district (fig. 1) is composed chiefly of lower Paleozoic rocks, divided into two stages. The lower stage (the Altachinian) consists of cemented silts, sand-

stones, and shales with occasional intercalations of carbonate rocks. The upper stage (the Nerchinsky Zavod) consists chiefly of dolomites and limestones. There are limited series of the Upper Silurian, represented by carbonate rocks and shales (the Blagodatian stage). There are individual, spotty Lower and Middle Jurassic formations consisting of conglomerates, sandstones, and shales. There are small bodies of granites and grano-diorites, and dikes and veins of granite porphyries, syenite porphyries, diabase, and lamprophyres.

The eastern portion of the district presents an extensive development of Lower Cretaceous deposits (sandstones and conglomerates) with isolated superincumbent Tertiary and lower Quaternary effusives (basalts and andesites). Micaceous schists and gneisses, dating partly from the Proterozoic and partly from the lower Paleozoic are exposed over a considerable area along the lower course of the Serebryanka River [4, 10, 11].

The occurrences of polymetallic ores [10, 11] are chiefly in the upper portion of the Altachinian and the lower portion of the Nerchinsky Zavod stages and lie chiefly in carbonate rocks. The ore bodies are chiefly in the form of lenses, veins, irregular pockets and pipes. Both homogeneous and disseminated ores occur. The main ore minerals are galena (argentiferous), sphalerite and pyrite. In smaller quantities, we encounter arsenopyrite and boulangerite, and, more rarely, other ore minerals. The gangue minerals are carbonates and, occasionally quartz.

Mixed ore formations are characterized by a mature and deep oxidation zone. In carbonate rocks, depth of oxidation attains 300 m or more (Tayninskoye, Trekhsvyatitskoye, and others), while in silicate rocks it is considerably less. Limonite is the dominant mineral in oxidized ores. Large quantities of manganese oxides are found. The lead- and zinc-bearing minerals are cerussite, anglesite, smithsonite, calamine, and others. The most important constituents in terms of industrial value are lead, zinc, and silver. A specific feature of these ores is their elevated arsenic and tin content. Generally, antimony is present; cadmium is common, and certain other rare elements are encountered. In addition to commercial ore accumulations, there are disseminated in the unweathered rock ore mineralizations and invisible alteration halos, revealed by high-sensitivity analyses. Width of the alteration halos attains 150 m and more. Dispersion halos [The Russian Geologicheskoy Slovar uses 'Pervichnyy (primary) oreol rasseyaniya' for 'alteration halo'; and, 'vtorichnyy (secondary) oreol rasseyaniya' for 'dispersion halo'. W. M.] are distinctly identifiable in eluvium and talus formations, underground and surface waters, and vegetations. Lead and zinc content in the halo epicenters



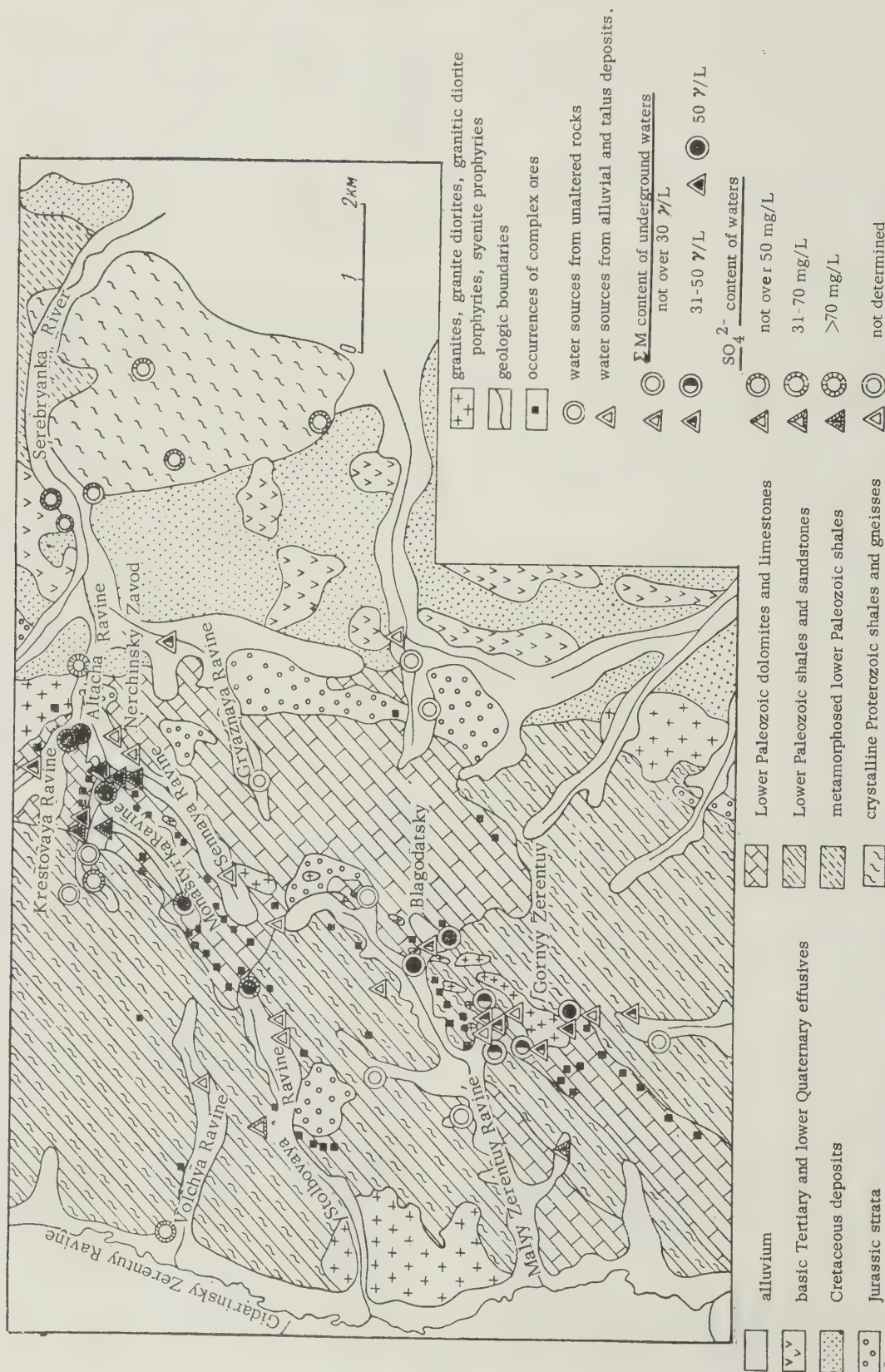


FIGURE 1. Geological map of the vicinity of Nerchinsky Zavod (after S.S. Smirov [10], with additions and corrections)

attains several tenths of one percent, with occasional readings of 1 percent or more, declining to hundredths of one percent toward the periphery of the halos. In many cases eluvial and talus halos may be traced downslope to the transition to alluvium.

#### DISPERSION HALOS IN MUD-CLAY STREAM-BED DEPOSITS

Dispersion halos of known formations were studied. Toward this end, specimen were taken from a number of exposed ravine formations. The ravines are typified by broad, flat bottoms and asymmetrical profiles; walls with southern exposure are steeper and covered with thin talus layers and steppe-type vegetation, while northern exposures slope from gradually, present thicker talus, and are overgrown with brush and liverwort. The depth of eluvium plus talus usually does not exceed 1.5-3.0 m, increasing to 5-8 m only on the lower portion of the slopes, although in spaces it attains 10-15 m and more. The alluvial deposits usually do not exceed 7-10 m, sometimes increasing to 15-20 m. Generally, the alluvial deposits are formed by destruction of the slopes; the role of deep erosion by river waters is negligible. Features of the erosive process permit the hypothesis that alluvium is formed principally by material brought down by intensive weathering of south-facing slopes. The degree to which composition of the alluvial (including streambed) deposits may reflect formations beneath them is not clear, although the alluvium is thin.

The territory over which the studies were made has been prospected in detail and has been mapped by metallometric surveys of the eluvial and talus deposits on a scale of 1:50,000 and larger. This made it possible to interpret anomalies found in stream-bed deposits; to ascribe to them the significance of dispersion halos; and, to coordinate them, on the basis of spatial correlations, with occurrences and metallometric anomalies on the slopes.

#### Method

##### Sampling

Samples were taken every 50 - 100 m (less frequently, the interval was 200 - 250 m) along the streambed. To reduce the influence of non-uniform distribution of the metals, each sample consisted, as a rule, of 3 or 4 specimens taken at spacings of 3 - 5 m, and sometimes of 10 - 15 m. The weight of the specimens was about 100 g each. Usually, mud was taken, although plastic clayey precipitates were encountered occasionally. Usually the muds contained considerable admixture of sand, at times in amounts sufficient to classify it as muddy sand.

Samples were taken from mud accumulations on spits and shoals right at the water line. To

take specimens from beneath the water is difficult, and was done considerably less often. Where the channel was grass-grown, soil from beneath plant roots was used. The point was that this soil was essentially the same mud, continually renewed by material coming down from above and but weakly affected by soil-forming processes. It should be remembered that ordinary muds consist in considerable degree of products resultant from the washing away of soils.

##### Processing

The processing of samples was performed as in ordinary metallometric survey. Samples were screened through 1 mm mesh, concentrated to 15 or 20 g and ground to powder (passing 150-200 mesh).

##### Sample analysis

Emission spectroscopy was performed with semiquantitative determination of seven elements: Pb, Zn, Ag, As, Sb, Sn, and Cd; characteristic of the polymetallic ore occurrences of the eastern Transbaikal. Analyses were run on an ISP-22 quartz spectrograph, by incomplete combustion of a sample in the hollow of a carbon electrode. The hollow diameter was 2.8 mm; its depth, 4 mm. Combustion conditions of 7-amp alternating current was used; combustion, of 60 seconds duration. Film used was spectrographic type I; sensitivity I. Elements were determined by the appearance and intensification of lines, followed by comparison with standard-specimen spectrograms of quartz; these contained the elements in the following percentages:

1; 0.3; 0.1; 0.03; 0.01; 0.003; and 0.001.

Appraisal of quantities of the elements was within the limits of adjacent gradations. Analysis results were expressed in hard figures within these limits.

These conditions allowed for determination of the elements to within the following margins of error (percentages):

Pb, 0.001; Zn, 0.01; Ag, 0.0001; As, 0.01; Sb, 0.01; Sn, 0.001; and Cd, 0.01.

Absence of systematic error was verified by control spectrum analysis in the Physical Analysis Methods Laboratory of VITR, and in the spectroscopy laboratory of the Nerchinsky Zavod geophysical party. No other methods were used to control the analyses. Reproducibility of the results falls within the limits of usual reproducibility for semiquantitative emission-spectrum analysis. The following conclusions are significant for interpretation of data from the samplings: a) reproducibility was high for element-content levels below the limit of analysis sensitivity (this held true

particularly for antimony, silver, and tin). Consequently, areas with low amounts of these elements were contoured correctly for the most part, and the percentage of falsely anomalous values is relatively small; b) the level of reproducibility was substantially lower when the element content was in the vicinity of the limit of sensitivity; this led to the missing of anomalous values; and c) when the element content was high approximately 0.1 percent and more), anomalous values are identified virtually without error. Because of the low reproducibility for spectrum-analysis results and the natural unevenness of distribution for the chemical elements, it is impossible to arrive at a reliable appraisal of anomalies by isolated samplings; and analysis of a series of samples is required.

### Description of the Halos

The curves in Figures 2 and 8 present sampling results for mud-clay stream-bed deposits in the most typical ravines. The anomalies, shown quite distinctly on the curves, are distinguished by the higher element content characteristic of polymetallic deposits: lead, zinc, silver, arsenic, antimony, and tin. The anomalies are correlated by position with deposits on the slopes and their halos of eluvium and talus. It is characteristic that in the vast majority of cases, the deposits reveal themselves in one or another way through composition of stream-bed muds.

In the headwaters of the stream flowing through the ravine illustrated in Figure 2, we see a clearly differentiated anomaly characterized by high lead (up to 0.02-0.03 percent) and zinc content (up to 0.01-0.02 percent) and the presence of arsenic in some samples. The anomaly is related to a deposit on the right-hand slope.

The sector downstream from the anomaly has considerably lower lead content (a few thousandths of one percent approximately). Zinc is found in but a few samples, and even more rarely, arsenic. In view of the fact that in barren areas, zinc and arsenic usually cannot be identified with spectrum analyses sensitive to within 0.01 percent, it may be concluded that they represent, in this instance, dispersion of ore material from the upstream halo. Such sectors, also encountered in quite a number of other cases, may be termed conveniently the train of the halo; and sectors wherein ore material from the slopes accumulates, the head of the halo.

Stream-bed deposits of the lower portion of the stream are characterized by markedly higher content of lead, zinc, arsenic (up to 0.1 percent and more), and of tin and silver as well. Two halos are distinguishable here: the downstream halo superimposed upon the train of the halo upstream. One of these halos results from erosion of ore material from a deposit along the

left branch of the ravine; and, possibly, also due to the addition of supplementary ore material from the right branch. The second halo locates a deposit near the ravine mouth; this halo continues right to the mouth of the stream.

Figure 3 presents a curve showing the element content of another ravine. Two halos are clearly distinguishable: The upper halo represents numerous ore occurrences surrounding a commercial deposit, most of which is beyond the ravine. It is notable for a high indicator element content. Below the head of the halo we see its train, identified by somewhat elevated content of lead (0.005-0.01 percent) and zinc. The downstream halo, of lower element content, marks a non-significant ore occurrence on the right slope.

Three dispersion halos are identified in the stream-bed mud-clay deposits of the ravine in Figure 4. The upstream halo relates to ore occurrences in the upper reaches of the ravine. It has a rather clearly defined train with comparatively high lead and zinc content (up to 0.03 percent). The middle halo represents a deposit high on the left slope; overlying its train is the downstream halo, representing a broad ore-bearing zone on the left slope. The origin of this halo is partly due to the fact that at this point there is an ore deposit right in the channel. The head of this halo is highly elongate resulting from erosion of ore material by a side ravine; an increased elemental content is observed in the mouth of this ravine. The train of the halo can be traced throughout the sampled portion of the stream channel.

Figure 5 shows a curve of somewhat different appearance. The channel deposits of a ravine illustrated here are characterized by generally higher lead, zinc, arsenic, and tin content related to numerous ore occurrences on the left bank. Against generally elevated background, we see anomalies representing halos in eluvium and talus slopes. The anomaly farthest downstream related to slags dispersed on the ravine floor over the territory of a settlement here.

The curve in Figure 6 is an example of generally increased element content without distinct anomalies extending a long way down the channel. The fact that the curve is of this nature, is explained by the fact that in the ravine, ore occurrences of insignificant size are so disposed as to result in virtually continuous delivery of ore material from the slopes to the channel. The distinct anomaly in the headwaters, where no ore occurrences are known, would appear to have been missed in the metallometric survey. The peaks in the lower portion of the ravine is related to the influence of a rich halo in the valley into which the particular ravine opens.

Figure 7 depicts a very extensive and rich



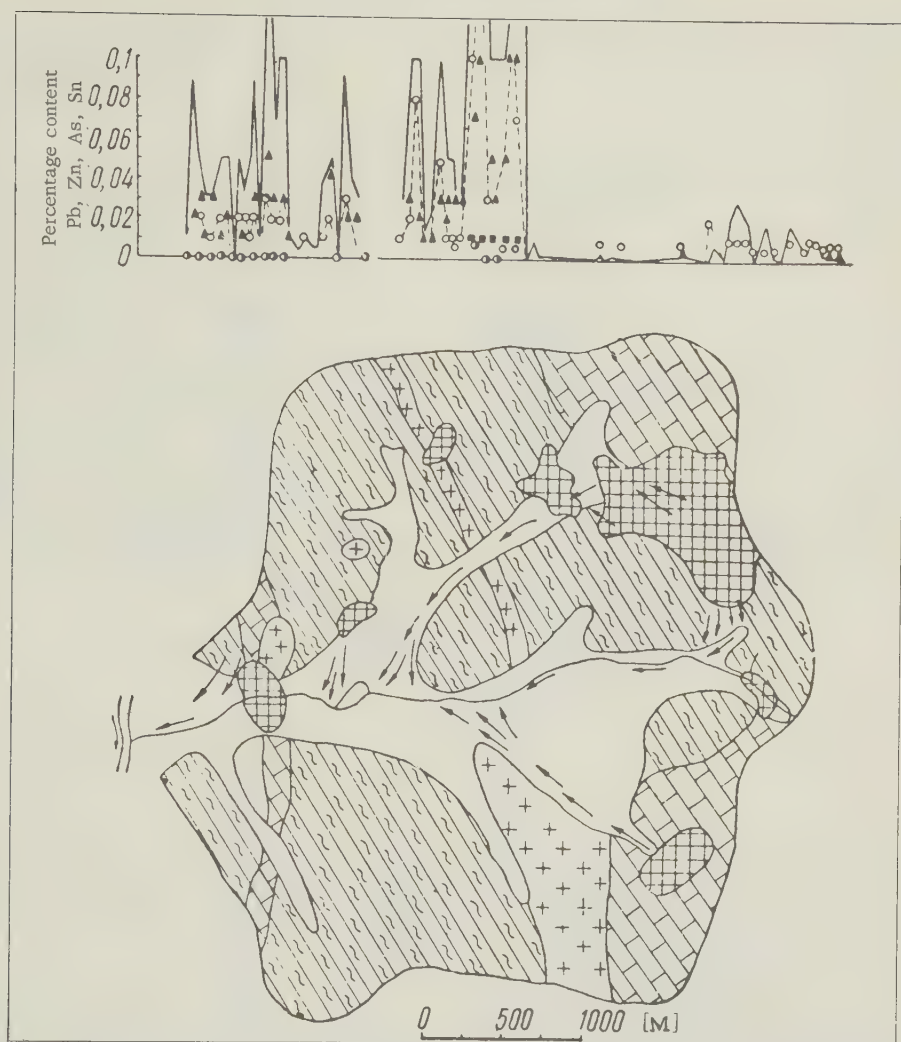





FIGURE 2. [Clearly differentiated anomaly, in mud-clay stream-bed deposit, related to deposit on right hand slope of ravine]


-  lower Paleozoic shales and sandstones
-  lower Paleozoic dolomites and limestones

 Jurassic sedimentation

 Cretaceous sedimentation

 granites, granodiorites, granodioritic porphyries, syenitic porphyries


 alluvium


 deposits and their eluvial and talus dispersion halos.

Key to curve: \

a) element content in streambed mud-clay deposits:

 lead

 zinc

 arsenic

 tin

 silver

 antimony

b) content in waters:

  $\text{SO}_4^{2-}$

  $\Sigma M$

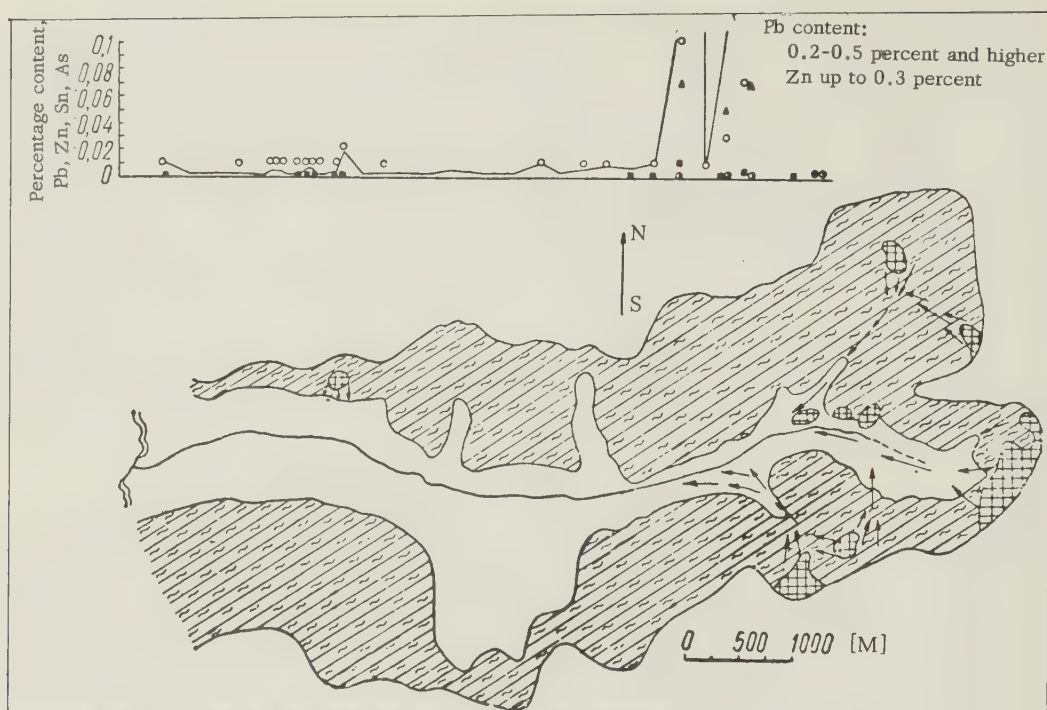


FIGURE 3. [The element content of a ravine; two halos are distinguishable]  
For key, see figure 2.

halo, related partly to natural dispersion of ore substance from deposits, partly to mine-tailings piles, and principally to slags from old silver and lead smelters here (i. e. the village of Nerchinsky Zavod). Total length of the dispersion halo in the mud-clay channel deposits is 15 km: 5 km of this length represents the head of the halo; 10 km, the train. At the left end of the curve there is a segment representing the background content of lead and other elements. At the head of the halo, the content of lead and zinc increases sharply (up to 0.1 percent; sometimes up to 0.5 percent and more). Antimony, silver, and tin are present; cadmium was found in individual samples. The train is characterized by elevated lead and zinc (0.01-0.04 percent), and also tin, content. At the confluence of the Altacha and Serebryanka rivers, an anomaly of unknown source, is superimposed upon the train of the halo. It is identified by increase in lead and zinc content, as well as in the appearance of arsenic and silver which are missing in the train.

In addition to these samples, there are instances of mud-clay stream-bed deposits in which dispersion halos cannot be identified, at least by the method of investigation we employ. Figure 8 illustrates cases of this type. As may be seen from the curves, a number of deposits shown on the map cannot be identified from samplings of stream-bed mud-clay deposits. In order to explain this fact, it is

necessary to bear in mind that the valleys are quite wide (up to 1.5-2 km at their floors); the deposits not presenting stream-bed halos are on the slopes a considerable distance away from the channels; moreover, they are, insignificant in size.

The halos we have traced in stream-bed mud-clay deposits, vary in size. The length of of the halos represents the sum of the lengths of their head and train. Naturally, the length of the halo head is dependent on dimensions of the mineralized area and on its position relative to the valley being explored. The trains of halos attain a length of 1.5-2.5 km, if we omit the exceedingly long train of the Nerchinsky Zavod halo (10 km) and the analogous halo train in the Malyy Zerentuy River; these are artificial halos caused by dispersion of mining and metallurgy products. Total length of halos we have traced varies from 800 m (for insignificant ore occurrences) to 4.5 km. A feature common to all the halos is unevenness of the distribution for elements therein; it is somewhat higher for the head portions of the halos and less for the trains.

In the vicinity of Nerchinsky Zavod, the majority of known deposits and occurrences have been mined to some degree. This poses the question as to what degree formation of dispersion halos may be a result of natural processes and to what degree related to erosion

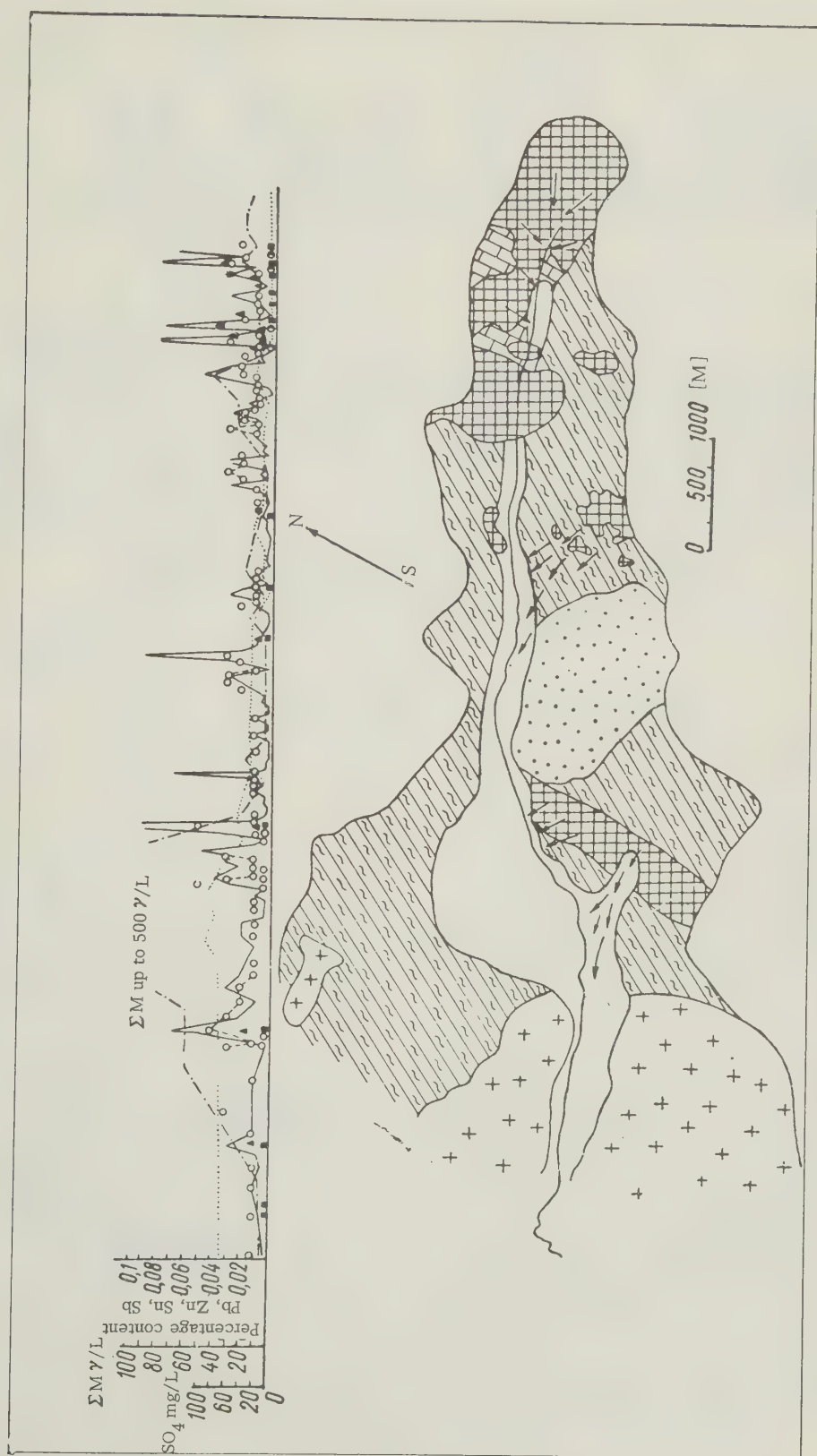


FIGURE 4. Stream-bed mud-clay deposit in a ravine; three dispersion halos are identified. For key, see Figure 2



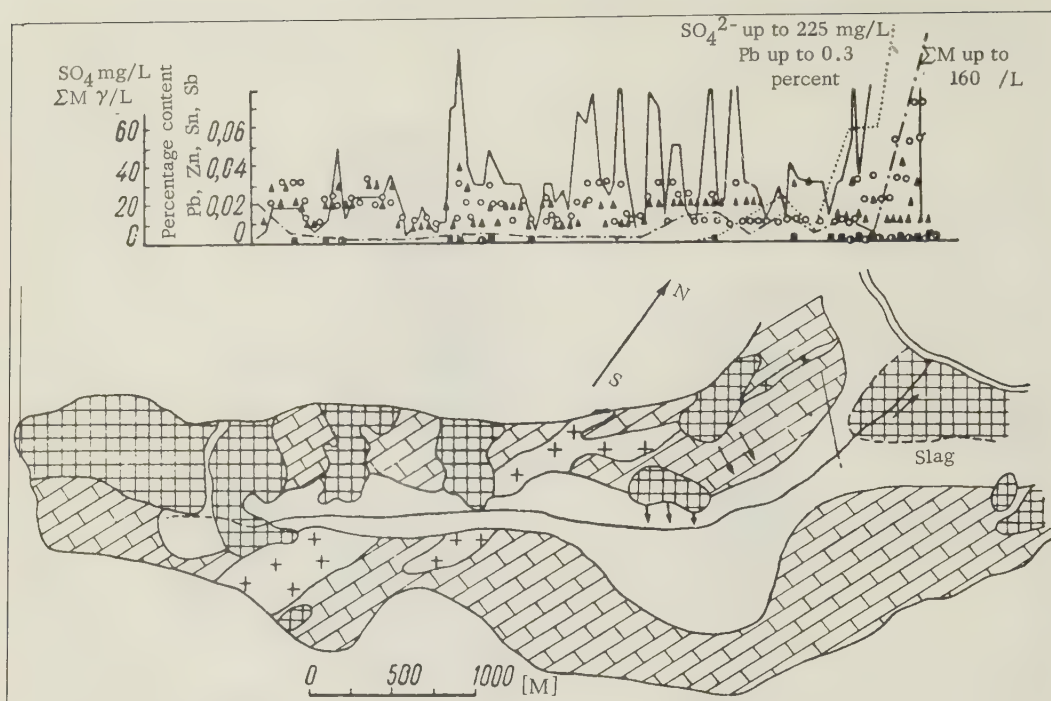


FIGURE 5. Ravine with channel deposits related to numerous ore occurrences on left bank of stream  
For key, see figure 2

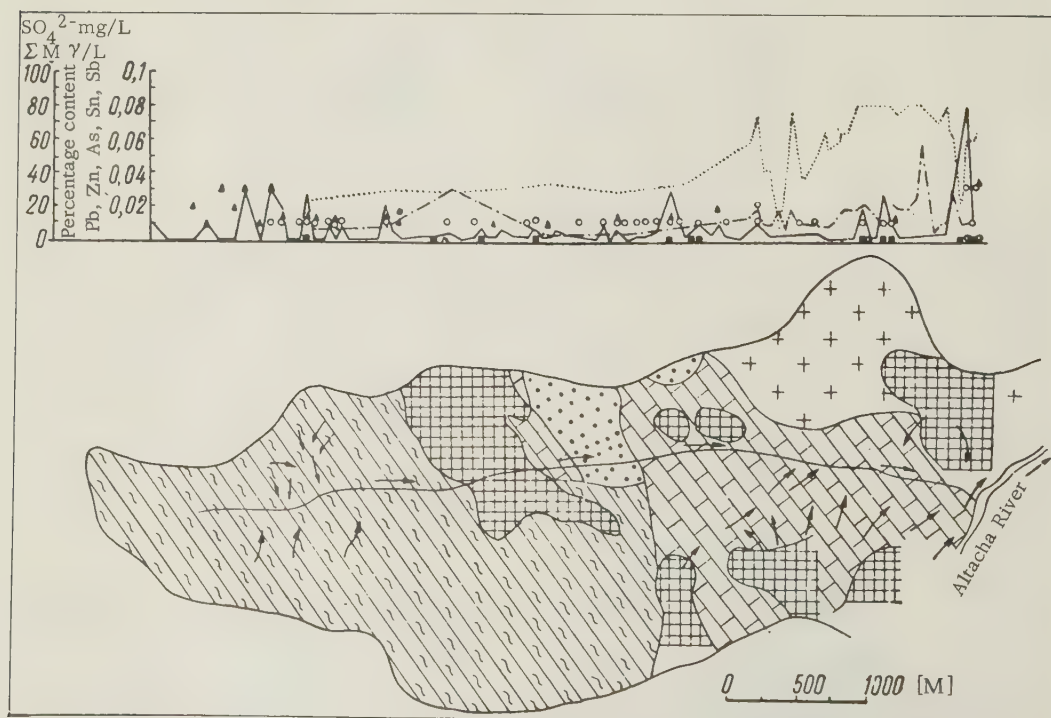


FIGURE 6. Example of generally increased element content without distinct anomalies, extending a long way down the stream channel.  
For key, see figure 2

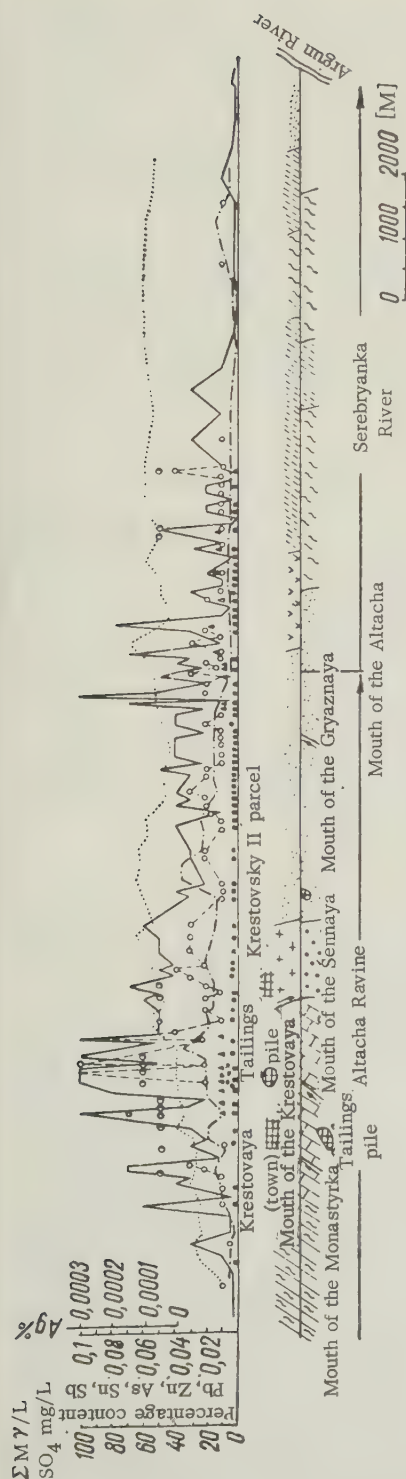


FIGURE 7. A very extensive and rich halo related principally to artificial (industrial) deposits, and partly to natural dispersion of ore substances  
For key, see Figures 1 and 2.

of ore matter from tailings piles from exploration and mining. Without making detailed examination of this question, we note that although the effect of mine tailings and industrial slags upon formation of dispersion halos is very strong in a number of cases, available data permit assertion that dispersion halos studied came into being, in the vast majority of cases as a result of natural processes independent of human activity.

#### Chemical Elements in Halos

Spectrum analysis (sensitive to within 0.001 percent) reveals the presence of lead in virtually all samples taken in eastern Transbaikalian polymetallic belt. In definitely barren areas, the content is usually a very few thousandths of one percent (0.001-0.003 percent), rarely as much as 0.005 percent or more). Lead content increases sharply in the vicinity of the deposits: Lead content amounts to hundredths or tenths of one percent; and, in single samples, to as much 0.5-1 percent and more in the head segments of stream-bed halos. Lead content in the trains of halos is usually a few hundredths of one percent; sometimes the trains are enriched in lead up to 0.005-0.01 percent. Lead halos may attain several kilometers (up to 4.5 km) length.

Zinc is always present in the stream-bed halos of polymetallic deposits; its content amounts to hundredths and tenths of one percent; and sometimes, to one percent and more. When sensitivity of the analysis is 0.01 percent, zinc is usually not found in barren areas. Appearance of even traces of zinc may signify a halo. The dimensions of zinc halos usually coincide with those of lead halos; but, many halo trains are distinguished by increase in zinc content alone, lead values remaining at background levels. Because of its geochemical properties, zinc is capable of forming elongate halos; dimensions for zinc halos, then, are clearly limited by inadequate sensitivity of analysis. It is to be borne in mind that in view of the increased zinc content of certain rocks (ultra-basic and basic magmatic rocks), and, as well, of the fact that zinc migrates in water with extraordinary ease, it is possible for zinc anomalies to come into being that have no relation to deposits.

Silver is an element that displays particularly characteristic halo behavior. At analysis sensitivity of the order of  $10^{-4}$  percent, silver usually is not discovered except in halos. Moreover, silver usually is determined only in the heads of halos; and, thus, indicates a deposit in the immediate vicinity. Silver content of halos amount to ten-thousandths, thousandths, and, considerably more rarely, hundredths of one percent. Silver was not found in certain halos.

Tin is often, but not always present, in the halos of polymetallic deposits of the Eastern Transbaikial. The content thereof in drainage-system muds, rarely rises above very few thousandths of one percent. Usually, tin is encountered only in the head portion of a halo; its appearance in the trains is rarer. Tin is not revealed in barren sections if analysis sensitivity is to 0.001 percent.

Arsenic is a common element in halos; its content in halos is expressed in hundredths, and more rarely in tenths, of one percent, but sometimes reaches one percent. As a rule, arsenic is determined only in the heads of halos. It should be noted that high arsenic content in drainage-system muds are sometimes observed outside of any spatial relationship with deposits, although usually it is not found in barren areas if the sensitivity of analysis is of the order of 0.01 percent.

Antimony is found in hundredths and tenths of one percent in the halos of many polymetallic deposits, but only in a small portion of the samples. When analysis sensitivity is 0.01 percent, it is found only in the heads of halos and, is not observed in the trains or barren terranes. Antimony is one of the metals whose presence is a most specific indication that the original body is in the immediate vicinity. Cadmium will be found in occasional samples. It is understood that the dimensions of the halos of these elements are delimited by analysis sensitivity.

The brief review of chemical elements in halos of polymetallic deposits, presented above, makes clear that the site and significance of identifications is not identical. Usually deposits are clearly identified by elevated quantities of lead and zinc in muds of stream-bed deposits of the valleys that reveal them, but elevated content of one element alone, particularly of zinc, may have no relationship to a deposit. Arsenic is found both in dispersion halos and outside of any relationship to deposits. The presence of silver, antimony, and cadmium in mud-clay stream-bed deposits is fairly sure evidence that deposits are present, but their halos are not very wide. To the foregoing must be added that these elements may be encountered in relation not only to polymetallic deposits, but with deposits of other types. Thus, the Belukhin tungsten deposit is characterized by elevated zinc and lead content, while arsenic is present in deposits of various minerals, etc. Therefore, in order to identify halos and interpret anomalies, it is most important that determination of a series of elements be determined simultaneously in the same samples. If this condition is met, correct identification of halos in stream-bed mud-clay deposits may be made often; the combination of elements will permit determination of the type of deposit with which the halo is associated.

### Summary

1. In the eastern Transbaikial polymetallic belt, characterized by a mature drainage system, rather intensive denudation processes, and relatively thin layers of loose sediment, polymetallic deposits on the slopes are easily discovered under existing conditions from dispersion halos in the stream-bed mud-clay deposits of the valleys that expose them.

2. Length of dispersion halos for small and middle-size deposits is up to 4.5 km; and, length of their trains, 2.5 km. These lengths may prove considerably greater if there is an increase in analysis sensitivity or if employment is made of special analysis methods developed to differentiate dispersion components of later deposition [9].

3. Simultaneous determination of a number of elements in the samples is desirable.

4. Drainage-system mud prospecting should be done in two stages to reduce volume of work: a) widely spaced samplings over the entire area to be covered in prospecting, with the purpose of discovering ore-bearing valleys. In the Nerchinsky Zavod district, 200 m spacings are quite adequate for discovery of ore-bearing valleys; b) more closely spaced samplings (50-100 m) of ore-bearing valleys and their segments which present good prospects; the object is to locate halos of specific deposits. Sampling should be combined with area-wide metallometric surveys.

### DISPERSION HALOS IN WATER

A study on dispersion halos in water was made in the Nerchinsky Zavod district. Both underground and surface waters were studied. The terrane under investigation is crossed by small rivers and streams; their flow is exceedingly uneven. Usually run-off is tens to hundreds of liters per second. During the dry season, the majority of these water courses dry up. Because the snow cover is thin, spring floods are insignificant. On the other hand, abundant rains come down in torrents during summer; frequent flash floods are common, and flow rises to the order of several cubic meters per second. In winter most of the small rivers and streams freeze to the bottom. The summer of 1956 was very rainy, and flash floods occurred more frequently than usual. They ceased, and a more or less stable rate of flow occurred only in September and October.

Ground water of the district falls within a single, connected aquifer. For hydrochemical prospecting it is convenient to differentiate them as follows: a) waters of unweathered rocks (comparatively deep circulation), and b) waters of alluvial and talus deposits (shallow circulation). In permafrost areas the latter type may be divided into subfrost and suprafrost waters.



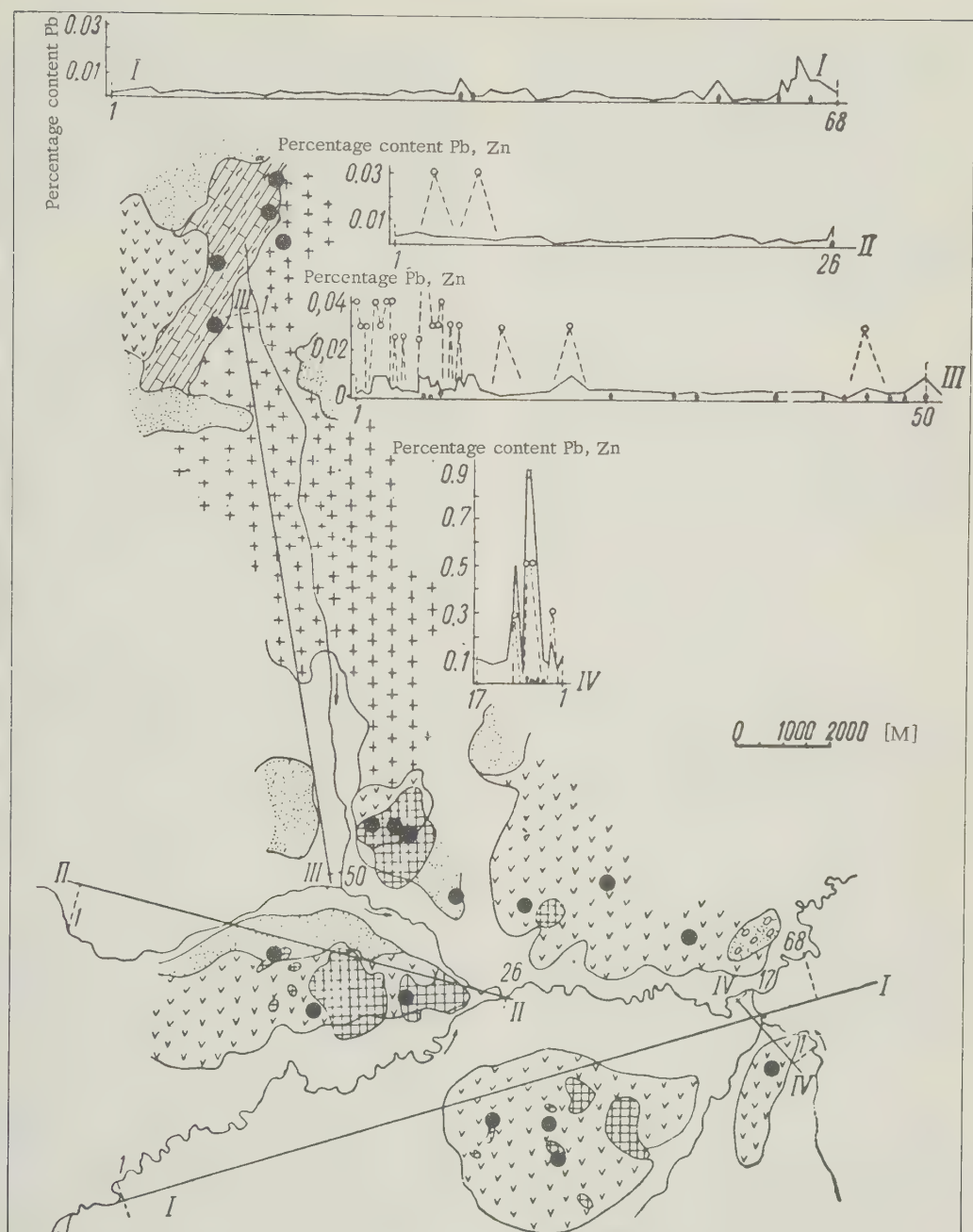


FIGURE 8. Dispersion halos cannot be identified from samplings of these mud-clay stream-bed deposits.

Waters of the unweathered rock circulate through fractures but sometimes concentrate in major faults. Represented by mixed material consisting of large fragments, sandy, and even finer particles, alluvial and talus deposits are quite permeable to water. In composition, the waters of the Paleozoic and Cretaceous deposits contain magnesium-calcium hydrocarbonate, while those of the Proterozoic rocks are sodium-sulfate bearing. Mineralization of waters usually does not exceed 400-600 mg/L; on rare occasions, it rises to 1 g/L, but sometimes it amounts to only 100-200 mg/L.

The number of underground water sources is not high: On the average, there is one spring from the country rock for each 10 km<sup>2</sup>. Springs of water from alluvial and talus deposits appear in the rainy season. During the dry season both these springs and many of those from unaltered rocks cease to flow.

#### Methods

##### Sampling

Samples of all water sources were taken from the country rock, and of rainy season water flows, from alluvial and talus deposits. Artificial water sources were opened, because the number of springs was inadequate. In addition, water samples were taken from prospecting pits made by auger.

Samples from surface water courses were spaced 50 to 100 and 250 m apart. In view of the narrowness of these streams (1.0-1.5 m, and, less frequently, up to 2 m), it made no difference whether the samples were taken from mid-stream or at either bank. Samples were taken from the subsurface layer in these streams (about 10 cm beneath the surface).

A half-liter bottle was used for sampling. Normal precautions against contamination were taken. Many water samples contained sediment particularly those derived from surficial streams, prospecting pits and bore holes. Therefore, samples were not acidified, the purpose being to avoid introduction into the water of metals that had undergone sorption by sediment particles. The bottles were plugged with rubber stoppers. Because of the possibility that samples may be contaminated by metals in the rubber, rubber stoppers are not generally recommended [2]. However, they were completely permissible in our work; for all practical purposes, extraction of metals from rubber does not occur where weakly alkaline waters, such as those of Nerchinsky Zavod district, are concerned.

#### Sample analysis

The basis of study of water dispersion halos was determination for total zinc, lead, and copper content of these waters (the so-called sum of metals,  $\Sigma M$ ). An increase in the sum of metals can identify a dispersion halos just as can an increase in content of each of these metals, individually. Moreover, determination of  $\Sigma M$  enjoys the advantage of considerably simplifying sample analysis.

The sum of metals was determined by means of diphenylthiocarbazone (dithizone). The determination was made by a method due to A. A. Reznikov [8] in a colorimetric version improved in the course of our work by I. P. Mulikovskaya [6]. The improved version envisages analysis of waters that are cloudy or contain much organic matter; provides for more complete determination of metals, including the portion sorbed during the analysis by glass of the separating funnel; and reduces danger of sample contamination during analysis.

Separate determinations of lead, zinc, and copper were run principally only for samples showing high  $\Sigma M$ . Zinc, lead and copper were determined by the LTI- [Tr.: the Leningrad Institute of Technology at Leningrad.] VITR method [1] with prior concentration of the metals by the sinking-particles method (on an ion exchanger), subsequent determination of zinc and lead in the concentrate by dithizone, and of copper by diethyldithiocarbamate.

Analyses conducted show the waters of the Nerchinsky Zavod district to be characterized by pronounced predominance of zinc over lead and copper content. The amount of zinc exceeds that of lead and copper by a factor of 5 to 10 or more. Usually, lead and copper content does not exceed the analysis error (not over 5  $\gamma/L$ ). Thus, under our conditions, the sum of metals determined by the dithizone method, represented zinc content in the majority of cases; only in individual instances with high anomalous  $\Sigma M$  values did the quantity of lead and copper exceed the analysis error.

Determination was made not only for  $\Sigma M$ , Zn, Pb, and Cu, but for  $SO_4^{2-}$  and pH of the waters. The  $Cl^-$  content was determined in a number of samples for the purpose of utilizing the  $SO_4^{2-}:Cl^-$  [2]; but this ratio did not prove characteristic of these waters and  $Cl^-$  determination was not continued.  $SO_4^{2-}$  determination was done, depending upon content, either by scale nephelometry; nephelometry in sediment-measuring test tubes; or by titration with trylon B [Tr.: Trylon B is sodium ethylene-

diamineetetraacetate (Large Soviet Encyc. ) and palmitate. The  $\text{Cl}^-$  was determined by titration with silver nitrate and by nephelometry. Determination of pH was made by colorimetry with a universal indicator and a scale for comparison. A portion of the samples was subjected to general analysis with determination of major mineralization components by a method described by A. A. Reznikov and E. P. Mulikovskaya [7].

#### Sensitivity and Accuracy of the Sum of Metals Determination

The variant of the dithizone method described was used to determine the sum of metals in the waters in concentrations of 5  $\gamma/\text{L}$  ( $5 \cdot 10^{-7}$  percent) or more. A distinction has to be made between the analysis accuracy of samples and accuracy of sampling in general; the latter value is of the greater significance in prospecting. Moreover, accuracy of sampling reflects errors due to the taking and transportation of samples. According to control-analysis data, the dithizone analysis method employed may be described as of adequate reliability and accuracy for quantitative purposes. In the overwhelming majority of cases the analysis error does not exceed + 25 percent. Errors exceeding the permissible, primarily the result of contamination, occur almost exclusively in samples with low  $\Sigma\text{M}$ ; they can be reduced to a minimum if the analyses are run carefully.

Accuracy of the samplings as a whole, verified by control samplings, is less than analysis accuracy. Overstated  $\Sigma\text{M}$  readings are noted in a number of samples with low metal content (contamination was responsible), and understated readings in others (because of sorption by glass of the flasks). Sampling is completely reliable in cases where metal content is distinctly elevated (approximately 50  $\gamma/\text{L}$  and above). At lower  $\Sigma\text{M}$  content there is the danger of non-permissible error levels; this probability rises as the amount of metal in the waters declines. For samples in which  $\Sigma\text{M}$  is less than 10  $\gamma/\text{L}$ , nonpermissible error levels are noted in 10 to 15 percent of the cases. On the whole, it may be concluded that, in the overwhelming majority of cases (not less than 80 percent), even samples with low metals content yield correct sampling results; and, waters with distinctively elevated metal content are defined with full reliability.

#### Variations in Zinc Content with Stream Behavior

A relationship is observed between  $\Sigma\text{M}$  of waters and their behavior as affected by atmospheric precipitation. Inasmuch as the  $\Sigma\text{M}$ , as found under the analysis method employed, usually represented zinc; obviously, it is possible to speak of the relationship between zinc content and behavior. Regularities for lead and copper may differ.

The relationship of zinc content to behavior was established most clearly for surficial water courses. Figure 9 shows this relationship for a point on an anomalous portion of the Altacha River. Despite scattering of the data, explainable in considerable part although not completely by analysis errors, the figure shows that distinct increase in zinc content was observed at high water levels resulting from rains. Content ranged from 14 to 60  $\gamma/\text{L}$ . Rise in zinc content of the waters during rainy seasons is apparently to be explained by the fact that sub-surface rocks become involved in water action; as a result, zinc enters the water as water-soluble compounds formed by intensive oxidation processes occurring at this level.

This fact is of great significance to hydrochemical prospecting, inasmuch as the limits of  $\Sigma\text{M}$  content fluctuations in waters of anomalous and background areas overlap. We do not possess data adequate for judgment as to variations in  $\Sigma\text{M}$  content in underground waters; but, it is entirely certain that they are not characterized by similarly sharp fluctuations.

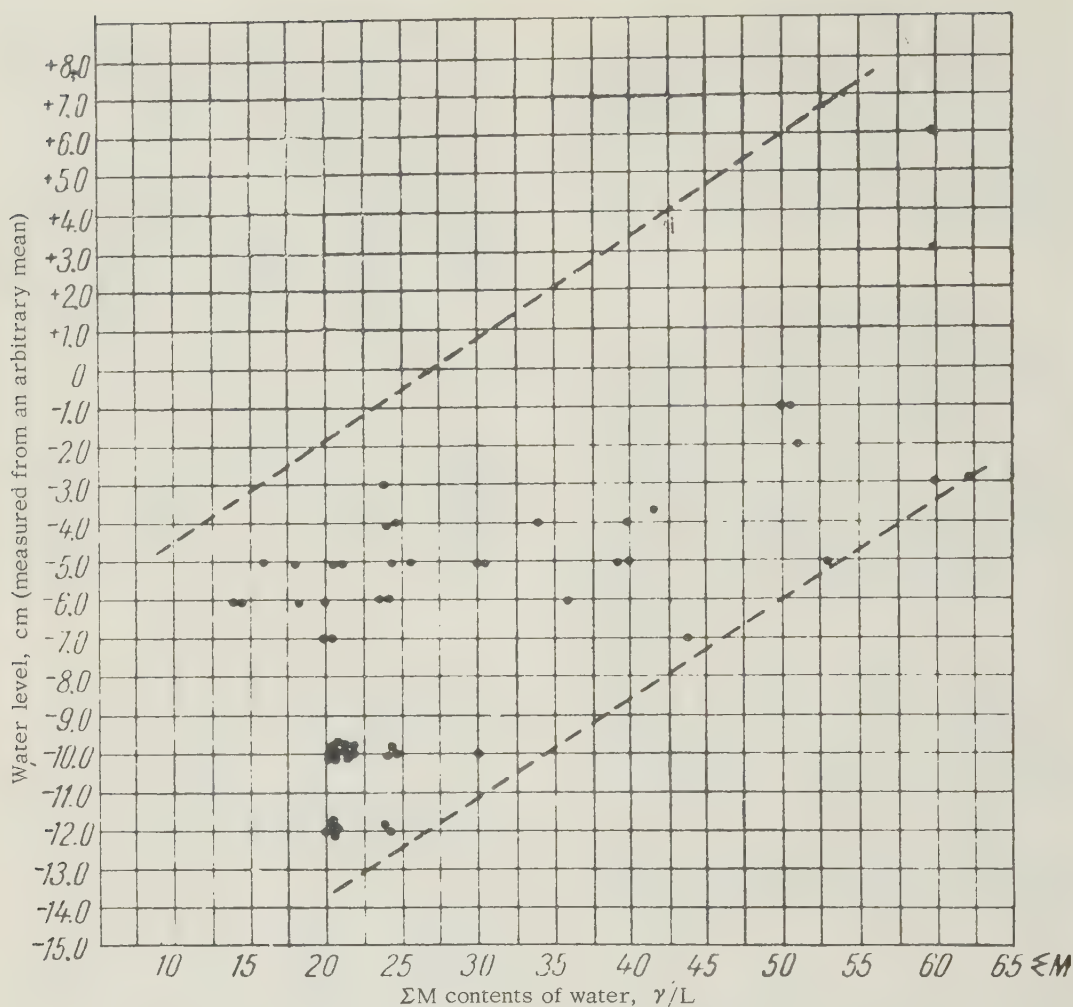
#### Dispersion Halos in Underground Waters

Figure 1 illustrates results of tests on underground waters. The major conclusion deriving from data presented in Figure 1 is that deposits are distinctly identified by high  $\Sigma\text{M}$  in ground waters. No single water source outside the mineralized area showed  $\Sigma\text{M}$  higher than 30  $\gamma/\text{L}$ . The  $\Sigma\text{M}$  of areas distant from deposits, where Altainian stage and Proterozoic crystalline schists are pronounced, show the  $\Sigma\text{M}$  content of waters to be within limits ranging from 5  $\gamma/\text{L}$ , which is the general case, up to 20  $\gamma/\text{L}$ . In areas of Cretaceous deposits,  $\Sigma\text{M}$  attains 25-28  $\gamma/\text{L}$  in spots, perhaps because the Cretaceous rocks came into being partly from the ore-bearing Nerchinsky Zavod series.

In ore-bearing areas,  $\Sigma\text{M}$  of the waters is rarely less than 30  $\gamma/\text{L}$ , and in most cases, exceeds 40  $\gamma/\text{L}$ . In no single instance was a  $\Sigma\text{M}$  of less than 20  $\gamma/\text{L}$  found in ore-rich areas and in immediate proximity thereto. In individual water sources, particularly in the vicinity of the larger ore deposits, the  $\Sigma\text{M}$  attained 100  $\gamma/\text{L}$  or more (up to 170  $\gamma/\text{L}$ ); readings of 50-60  $\gamma/\text{L}$  were not rare. In mine waters,  $\Sigma\text{M}$  often exceeds 200  $\gamma/\text{L}$ , and in some springs brought into being by mining operations it attains 2000  $\gamma/\text{L}$ .

Due to the small number of water sources, ground-water samplings do not reveal all deposits by any means; but, on the whole, the ore-bearing zone is defined quite definitely. High  $\Sigma\text{M}$  in underground waters was found at horizontal distances of up to 1.5 km from deposits. However, this does not correspond with complete accuracy to distances that the metals migrate, as the deposits are surrounded by dispersion halos in the country rock and in the



FIGURE 9. Changes in  $\Sigma M$  of Altacha River waters in agreement with water level

eluvium and talus; the widths of these halos were not determined in all cases.

It should be noted that no pronounced differences were found between  $\Sigma M$  in the waters of the eluvium and talus, and those of the country rock.  $\Sigma M$  in the alluvial and talus deposits also is within the limits of gradations indicated above. Apparently, this is to be explained by the fact that zinc undergoes ready and rapid transport from the rocks to the waters under the conditions of the oxidation zone.

Because of the inadequate number of springs from the country rock, this fact is of major importance in prospecting in that it makes possible prospecting by means of springs, which appear in abundance during rains, in alluvium and talus, or, by artificial exposure of these waters, which lie only a short distance beneath the surface.

The  $SO_4^{2-}$  content is a significantly less specific indicator of ore deposits. The quantity of  $SO_4^{2-}$  in underground waters in the Nerchinsky Zavod district fluctuates between 5 mg/L (sometimes less) to 200-260 mg/L. Moreover, a high  $SO_4^{2-}$  content is found in waters both near deposits and on obviously barren terrane. On the other hand, the quantity of  $SO_4^{2-}$  is quite low in some underground-water sources near deposits which display markedly elevated  $\Sigma M$ . This is convincingly evident from examination of the  $SO_4^{2-}$  data in Figure 1. The neutralizing effect of carbonate rocks has a powerful effect upon the  $SO_4^{2-}$  content of the waters. In this connection, data on  $SO_4^{2-}$  content of ore waters from the Ivanovo and Yekaterino-Blagodat mines is of pronounced interest. Waters of the Ivanovo mine, where rocks containing intrusive ore bodies are hornblendites and schists, contain 75-90 mg/L of  $SO_4^{2-}$ , the  $\Sigma M$  being 100-170  $\gamma/L$ . Waters of the Yekaterino-Blagodat mine, where the ore bodies are

in carbonate rocks, contain 4 to 16 mg/L of  $\text{SO}_4^{2-}$ ; only in occasional instances does this figure reach 50 mg/L in the immediate proximity of ore bodies, while  $\Sigma\text{M}$  reaches 300-400  $\gamma/\text{L}$ .

Apparently,  $\text{SO}_4^{2-}$  has little value as a prospecting indicator for ores in carbonate rocks and does not identify uniquely deposits even in silicate rocks. Nor may acidity of the waters be employed, practically, as an indicator for prospecting. Waters of the Nerchinsky Zavod district are weakly alkaline for the most part; their pH is in the range of 7.2-8.4, and, in rare cases, less (as low as 6.2). No noticeable reduction in pH related to the presence of deposits has been observed.

### Dispersion Halos in Surface Waters

Discovery of dispersion halos in surface waters is complicated by the fact that their metal content, in general, is very small; identification of an anomaly requires high sensitivity and special care in sampling and analysis.

During long dry periods,  $\Sigma\text{M}$  of areas at a distance from ore deposits does not exceed 5  $\gamma/\text{L}$ .  $\Sigma\text{M}$  reading of 10-15  $\gamma/\text{L}$  signifies anomalies caused by deposits. During the rainy seasons,  $\Sigma\text{M}$  of the halos increases by 100 percent and more, while there is a simultaneous rise in  $\Sigma\text{M}$  to 10-20  $\gamma/\text{L}$  or more in areas where no halo is present. With this level of content, discovery of halos is an easier matter provided that an analysis method for cloudy waters is available, as river waters carry a considerable amount of sediment during these periods. Furthermore, if it be considered that deposits high on the slopes, exempt from influence of the hydrosphere during the dry season, are washed down during the rainy season, then advantages of performing surveys of surficial waters during the rainy periods become obvious. Practical prospecting under the conditions of the Eastern Transbaikalia is complicated, however, by sharp and rapid changes in  $\Sigma\text{M}$ , referred to above, accompanying frequent, very heavy rains.

Data on dispersion halos in surficial waters adduced below pertain to a period, starting in the second half of the season of August to October, 1956; at that time, there was comparatively little precipitation in the area under investigation.

Curves of  $\Sigma\text{M}$  and  $\text{SO}_4^{2-}$  content in surface waters are presented in Figures 4, 5, 6, 7, and 10. The curves show that quite a number of deposits is clearly identified by elevated  $\Sigma\text{M}$  of surficial waters. The curve in Figure 4 shows three anomalies representing ore-bearing sections in the upper half of a ravine, and a fourth anomaly identifying an ore-bearing zone

in the lower half of the ravine. It should be noted that the very high  $\Sigma\text{M}$  of this anomaly (up to 500  $\gamma/\text{L}$ ) relates to the fact that mine waters rich in metal empty here directly into the rivulet. Figure 7 illustrates an elongate halo (9 km) corresponding to the halo in mud-clay bottom deposits described above.

Furthermore, deposits are not accompanied in every instance by dispersion halos in surficial waters. In the ravine depicted in Figure 10, elevated  $\Sigma\text{M}$ 's are noted only in relation to deposits in the headwaters. Other deposits do

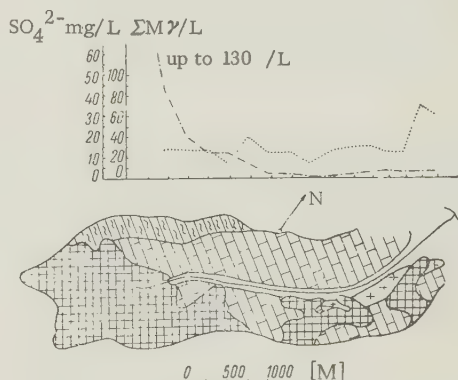


FIGURE 10. [Elevated  $\Sigma\text{M}$  noted only in relation to deposits in headwaters of this ravine.] For key, see Figure 2

not induce increase in  $\Sigma\text{M}$  of the rivulet waters. An analogous picture is observed also in the ravine presented in Figure 5. An increase in  $\Sigma\text{M}$  is noted only for the lower half of this ravine, because of ore occurrences and slags present there. Deposits of the upper half do not affect  $\Sigma\text{M}$  of the stream waters. Apparently this relates to the fact that when sampling was done in the dry season, deposits, at this point high on the slopes, were beyond the sphere of activity of the waters.

The conclusions relative to  $\text{SO}_4^{2-}$  are analogous to those made above for underground waters. In a number of cases, there is an increase in  $\text{SO}_4^{2-}$  content of surface waters related to deposits (figs. 7, 4, 6). This does not occur in other cases (fig. 10). Finally, an increase in the  $\text{SO}_4^{2-}$  content, not connected with deposits, is observed. Despite the fact that  $\text{SO}_4^{2-}$  is not a definite indicator for the presence of deposits, it is well to utilize it in hydrochemical prospecting. The point is that  $\text{SO}_4^{2-}$  halos are very extensive and stable. This is visible particularly in the curves of Figures 7 and 4 where the  $\text{SO}_4^{2-}$  anomaly is considerably longer than the  $\Sigma\text{M}$  anomaly. The  $\text{SO}_4^{2-}$  halo in the Altacha and Serebryanka rivers near Nerchinsky Zavod continues with no noticeable diminution for 20 km to the Argun

River. In prospecting, special attention should be given to the head portions of  $\text{SO}_4^{2-}$  anomalies; these portions should be subjected to careful sampling for  $\Sigma\text{M}$  and other components indicating presence of deposits.

### Summary

1. Polymetallic deposits are identified very distinctly by high  $\Sigma\text{M}$  content of underground and surficial waters. In view of the inadequate number of springs, and, as well, the fact that deposits and their dispersion halos are not all necessarily in reaction with the hydrosphere during the period when sampling is conducted, hydrochemical prospecting does not reveal all deposits. However, ore-bearing areas and districts are identified to an adequate degree of assurance.

2. Our work did not turn up any false  $\Sigma\text{M}$  anomalies; i. e. anomalies not accompanied by ore deposits. It must be borne in mind, however, that the so-called sum of metals is, in point of fact, zinc content; as zinc is widely disseminated in the natural waters. Therefore, it is desirable to run control checks of  $\Sigma\text{M}$  anomalies to determine presence of other components which may be indicators of ore deposits.

3. Sampling of alluvium and talus waters yields the same results as does sampling of waters from country rock. Hydrochemical prospecting of ground waters should be conducted during rainy periods; at that time, a large number of springs appear in alluvium and talus, permitting a larger percentage of deposits to be discovered.

4. Prospecting of surficial waters during the rainy seasons also has its advantages. However, where there are frequent brief rains, prospecting is complicated by the difficulties of interpreting the sampling results.

5. The success of hydrochemical prospecting is dependent substantially upon the care with which it is performed and the taking of measures against contamination of samples as they are obtained and during analysis. This is particularly true for surveys of surficial waters.

### CONCLUSION

The data adduced above testify to the dependability of polymetallic-deposit prospecting by sampling streambed mud-clay deposits, as well as underground and surface waters, under conditions in Eastern Transbaikalia.

The prospecting of drainage system muds has the advantage that a comparatively small number of samples is needed to discover ore-bearing districts, and portions thereof, offering good prospects. Judging by preliminary data the number of samplings required is at most, one-

tenth that required for areal metallometric survey of eluvium and talus on the 1:50,000 scale usually employed for these purposes. In addition, sampling of drainage-system muds offers good knowledge of the depths; muds of underground and surficial waters may reflect blind deposits or deposits covered by heavy overlays of loose matter, not discoverable by metallometric surveys of talus.

In addition to information on the depths that this sampling is recognized generally to provide, another advantage of hydrochemical prospecting is simplicity of analysis; bulky special equipment, sources of electric power, haulage of fuel, etc. are not required, with the result that analyses may be conducted under conditions obtaining in any field party.

The major field of application for these two methods is in the initial stages of prospecting operations (on 1:100,000 and smaller scales). Principal advantages of these methods; i. e. possibility of rapid discovery of ore-bearing districts, and portions thereof in large territories and that of running analyses under field conditions (when hydrochemical prospecting is employed), are evidenced specifically in this stage.

Prospecting on a small or medium scale usually is directed toward discovery of deposits not of some specific mineral, but of a mineral complex. In this connection, it is necessary to verify dependability of various methods relative to various commercial and genetic types of deposits of a number of metals. Data obtained in 1956 on the Olekma River headwaters by P. A. Petrov (Chita Geological Bureau) bears witness to dependability of drainage-system mud prospecting for molybdenum. Our own preliminary data testify to the possibility of using this method to reveal certain types of fine ore deposits (stockworks of quartz and tin ore). The list would appear to be capable of substantial expansion.

The potential range of occurrences for discovery by the hydrochemical method is not large at present, in view of the fact that analysis methods for natural waters, modified to meet hydrochemical prospecting conditions, have at this writing been developed for but a small number of elements. The dithizone analysis method we employed, with determination of the sum for zinc, lead, and copper, is suited to prospecting for polymetallic deposits and, as well, for certain others in which these elements are present as impurities. Hydrochemical prospecting practice requires elaboration of analysis methods, for native waters, so that a number of elements can be determined at once. Some progress in this direction has been made. However, methods proposed, for example that of VITR, have not been checked out under field conditions.



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# SPECTROGRAPHIC AUROMETRIC SURVEYING AS A METHOD OF PROSPECTING FOR GOLD ORE DEPOSITS NOT ACCOMPANIED BY MECHANICAL HALOS (PLACERS)<sup>1</sup>

by

N. I. Safronov, V. V. Polikarpochkin and A. A. Utgof

• translated by William Mandel •

## ABSTRACT

At present, metallometric surveying is employed in prospecting for most of the commercially useful metals; for gold, however, this method had not been found practical. It has been assumed that all gold deposits are identifiable, by gravimetric survey, from their mechanical dispersion halos; and, in that gold is inert, identifiable in the supergene zone by its resistance to chemical change and migration. In addition, there have been available no analysis methods comparable in sensitivity and efficiency to those of gravimetric survey. Analysis methods for gold must show content of at least 0.05 grams per ton ( $5 \times 10^{-6}$  percent); and a safety factor, in addition, of twice that amount, or  $2-3 \times 10^{-6}$  percent. Standard emission-spectral analysis has proven inadequate as has chemical analysis with respect to time consumption, expense, and degree of sensitivity. A combined chemical-adsorption spectral analysis of metallometric gold samples tested by VITR in 1956 was found to have the sensitivity (0.03 grams per ton, or  $3 \times 10^{-6}$  percent) as well as economy of operation necessary for general use. Essentially, this analysis process involves enrichment, accomplished in two stages, of a sorbent material with gold from analysis samples. The gold-enriched sorbent is analyzed by ISP-22 or ISP-28 quartz spectrograph, and the results interpreted visually by comparison of spectra with those of the standard specimen (prepared immediately preceding the analysis process). In 1956, VITR completed a successful field-control test of this combined-analysis method in eastern Transbaikalia; gold dispersion halos, undetected previously by the usual spectral-analysis method (without the concentration process), were located near the deposit. Concentration of gold in these halos was 0.05 grams per ton. Further investigation may make it possible to prospect for gold by testing certain plant species; thus utilizing the data on gold content of plants. -- D. D. Fisher.

At present, metallometric surveying is used in prospecting for primary ore deposits of almost all commercially important metals; only a few metals are not being encompassed currently by its use. Gold is one of them.

Three factors are responsible for this situation:

1. The deeply rooted view that gold-ore deposits will always produce mechanical dispersion halos invariably identifiable, of course, by gravity concentration survey.

2. The entrenched view that gold, as a metal of exceptional inertness in the supergene zone, [Tr.: The Russian text uses the term hypergene, a term due to Fersman, which is broader in concept than "weathering", which it approximates. See *Geologicheskii Slovar'*], is not subject to any chemical changes and migrations in that form.

3. The absence, until recently, of highly sensitive and correspondingly fast sample analysis methods for gold which can compete with the gravity concentration method and can

serve as the foundation for mass determinations of this metal under natural conditions, as required in metallometric surveying.

Let us examine these three factors in the light of most recent data. The first concept was given its most distinctive expression in a methods handbook for geologic survey and prospecting, compiled by a group of VSEGEI geologists and published by Geoltekhizdat in 1954 [1], which states: "The stability of native gold in natural conditions is the reason for the... exceptional significance of secondary - placer - ore deposits. For this very reason, the major prospecting sign for most gold deposits is presence of native-gold particles in unconsolidated decomposition products of primary source materials" (p. 280). And, although subsequently (p. 283) attention is directed to the fact that "all primary deposits do not, by any means, result in placers of commercial significance", nevertheless the following final conclusion is drawn (p. 283): "However, the most specific and accurate prospecting indication for all types of gold-ore deposits is dissemination of native gold in unconsolidated sediments. The gravity concentration method remains thus valid even for districts with widespread deposits of dispersed or chemically combined gold, as native gold is almost always encountered even in such deposits or in their oxidation zones."

<sup>1</sup> Translated from *Spektrozolotometricheskaya syemka kak metod poiskov zolotrudnykh mestorozhdeniy ne soprovozhdayemykh mekhanicheskimi oreolami (rosspyami)*, in: *Novoye metodiki i tekhniki geologorazvedochnykh rabot*, Sbornik I: Leningrad, Gosoptekhizdat, 1958, p. 100-108.

Thus, the foregoing [information] orients prospectors to discovery of gold deposits through their mechanical dispersion halos, employing

gravity concentration. However, in the light of the most recent data, this recommendation cannot be regarded as covering all cases. In point of fact, verified data have been obtained in the northeastern USSR and in Yakutia [2] pointing to the existence of primary sources of dispersed gold associated with hornblendes in the northeast and with jasperoids in Yakutia; these sources were accompanied by placers (or, in other words, by mechanical dispersion halos) and therefore missed by a gravity concentration survey. There is reason to assume that these data must be given very serious consideration, in that they may indicate the existence of a natural phenomenon of significantly wider distribution and practical significance than can now be conceived of on the basis of the present isolated, accidentally acquired moreover, pieces of information. We remark in passing that discovery, in recent years, of commercial deposits of molybdenum and other metals, bearing metal in invisible form, constitutes direct testimony in favor of this viewpoint.

Thus, the requirement that geological exploration be multifaceted and reveal all possibilities in the area for bids limitation of prospecting for gold deposits solely to gravity concentration, and, poses the problem of supplementing exploration with methods that allow for discovery of gold occurrences not accompanied by mechanical halos.

Without pausing for detailed examination of the second of the previously listed factors that inhibit introduction of aurometric surveying into prospecting, we note that in recent years the Czech investigator I. Babichka [3] has obtained very interesting information on gold behavior in the hypergenesis zone. It is he who has demonstrated the capacity of gold in nature to yield invisible, "chemical", or, to use the terminology employed, salt-dispersion halos where gold is found, according to his hypothesis, in colloidal form. These halos are found in the rhizosphere (the soil layer containing roots) or in plants (particularly horsetails).

Thus, there are no theoretical reasons for not prospecting for gold deposits by seeking their invisible dispersion halos in the form of "chemical" salts. There can be no question but that this method should be directed first to prospecting gold-ore deposits containing the metal in dispersed, "invisible" form; i.e. incapable of producing mechanical halos and therefore missed in gravity separation surveys.

In the field of rapid analysis methods, we describe below a special method of metallometric sample investigation for gold in which spectral analysis figures in the final stage. In sensitivity, speed, and cost, this method is now fully worthy of recommendation for large-scale practical use. The principles of this meth-

od were elaborated at Dalstroy [4], there, it was first tried out on a large scale in the final testing of gold-ore samples.

The end result is that aurimetric surveying may be recommended as a prospecting method for gold-salt halos, to be used in tracing primary invisible-gold sources. It is essentially analogous to the familiar metallometric surveys whose prime purpose is to prospect deposits responsible for salt and mixed-type dispersion halos of other metals.

Let us go somewhat into greater detail concerning the bases for analysis of aurometric samples, in view of their relative novelty. We know that the general occurrence of gold is defined by a figure on the order of  $5 \times 10^{-7}$  percent, or 0.005 g/t. For a primary deposit to be of commercial value, the minimum content required is 5 g/t ( $5 \times 10^{-4}$  percent). Thus, an economic deposit must have a tenor about 1,000 times as great as the average occurrence in nature. Experience has shown that, for most non-ferrous metal deposits, tenor of the metal in the dispersion halo is lower by one or two orders of magnitude, than that of the deposit. This means that the tenor of gold in a halo will be greater by a factor of 10 or more, than its average occurrence, inasmuch as we may expect properly, dissemination halos to show content of not less than 0.05 g/t ( $5 \times 10^{-6}$  percent). In accordance with the foregoing, an analysis method for gold samples must show sensitivity of not less than 0.05 g/t ( $5 \times 10^{-6}$  percent), and, should provide a safety factor of at least twice that, or, in other words, have 0.02-0.03 g/t ( $2-3 \times 10^{-6}$  percent) sensitivity.

We know that sensitivity of standard emission-spectral analysis for gold is 10 g/t ( $10^{-3}$  percent). It is obvious that, unmodified, this type of analysis is inapplicable to the purposes in question, inasmuch as its sensitivity is inadequate by a factor of about 400 for that requirement. The test-tube analysis widely employed in laboratory practice is expensive, time-consuming, and of inadequate sensitivity: Under the best of conditions it identifies quantities of not less than 0.1 g/t, this is 3 - 5 times the amount to be expected in halos. This type of analysis also is unsuited to metallometric purposes.

Below we describe the combined chemical and adsorption [Ed.: Khimiko-adsorptsionnyy] spectral analysis of metallometric gold samplings as tested in experimental studies by VITR in 1956. The essence of this method is the following: a) a portion of the sample is treated with aqua regia, causing all the gold to go into solution; b) the resultant solution, separated from the sample, is treated with a sorbent that absorbs gold from the solution. When proper weight specimens of initial sample and sorbent are used, the first stage of gold con-



centration in the sorbent is attained; c) the sorbent is then calcined to constant weight, yielding the second, and final, stage in gold concentration; d) gold-enriched ash is subjected to standard emission spectrography and the analysis results are recalculated for the size of the initial sample.

Use of proper quantities by weight of initial sample and of sorbent allows for the degree of enrichment required in the ash for use of spectral analysis with the confidence that recalculation of metal values for the initial sample will provide adequate sensitivity. Simple mechanization of all stages in the work yields rapidity of analysis, thus rendering the method suitable for general use.

As proved in practice, sequence to be followed in the combined chemical and adsorption spectral analysis for gold having a sensitivity of the order of 0.03 g/t ( $3 \times 10^{-6}$  percent), is:

a) The metallometric sample is ground and concentrated in the usual way to 150-200 mesh size, and to approximately 50 g weight.

b) The ground sample is calcined in a muffle furnace at 550-600°C. The specimen for calcining may be measured safely by means of a graduated vessel, provided that the residue after calcining is not less than 12.5 g of substance. Calcining is run for 2 hours. Vessels used for calcining are flat porcelain boats providing for a layer of material no thicker than 5 mm. Attention is drawn to the need for careful performance of the calcining operation, which has the object of converting iron in the sample into insoluble form and of burning off the carbon completely. However, the calcination temperature must not be excessive (not over 550-600°C), to prevent the gold from volatilization, which may occur even at this low temperature, if the gold is in colloidal form. Other investigators also note this [3].

c) A 12.5 g sample is taken from the material thus calcined. This may be done also by using a calibrated vessel or by weighing on apothecary's scales.

d) Each sample is poured into a 120-150 cc cylindrical flask with ground-in stopper. Should such flasks be unavailable, ordinary bottles or druggist's flasks of the same capacity, with rubber stoppers, may be used.

e) Into each flask, after the sample it contains is wetted with 10 cc water, there is poured 16 cc of 3:1 aqua regia (12 cc hydrochloric acid, specific gravity 1.18-1.19; and 4 cc nitric acid, specific gravity 1.35-1.38). The aqua regia must be prepared immediately preceding the analysis; not in advance.

If a power drum is available (design is im-

material but the axis of rotation must be horizontal), the closed flasks or bottles are placed therein (horizontally!) with their contents, and the drum is rotated at 10-12 rpm. This results in good mixing. If this procedure is followed, the total time of contact between specimen and aqua regia does not exceed 2 hours.

If a mechanical mixer is lacking, contact should be permitted to continue for 6-8 hours, with shaking every 20-30 minutes. It is necessary to prevent the contents from spreading along the vessel walls without contact with the liquid.

f) After the specimens are treated with aqua regia, the flasks are filled with water up to their necks; then the solutions are allowed to stand until lightly cloudy. This has no negative effect on further procedure.

g) Solutions containing the specimens that have been permitted to settle, are poured off into 120-150 cc beakers, each holding 750 mg of sorbent. The sorbent to be used is activated charcoal of the type used in gas masks, ground to -20+40 mesh, or industrial ion exchanger made by sulfuric acid treatment of a natural carbon. Ten minutes of contact between the sorbent and the solution is adequate; slight cloudiness in the solution does not interfere with the process. The sorbent should not be weighed but measured by means of a graduated scale. This operation results in the first stage in gold enrichment of the sorbent, at a ratio of 12.5:0.75 or, roughly, 17 to 1.

h) The used solution is decanted off the sorbent which, if it is cloudy, is washed 2 or 3 times with water. There need be no fear that gold will be washed out of the sorbent. The sorbent is then dried in the same breaker to atmospheric humidity, and, is immersed in a porcelain crucible of 1-2 cm<sup>3</sup> volume. It is worth noting that tap, well, or even river water, provided that it contain no gold in solution, may be used for all purposes of wetting, dilution, washing, etc.

i) The sorbent in the porcelain crucible is reduced to ash in a muffle furnace at 600-700°C temperature for 30 minutes to an hour. The ash weighs approximately 35 mg. This operation yields the second degree of gold concentration, which is increased about 20-fold relative to the sorbent. Ultimate enrichment, relative to the initial specimen, is  $(\approx 17)(20) \approx 340$  times. This means that with spectral analysis sensitive to 10 g/t it is possible to determine content on the order of  $10:340 \approx 0.03$  g/t in terms of the original specimen.

j) Sorbent ash thus obtained is burnt in a 7-amp DC or AC electric arc. Spectrally pure carbon must be used for the electrodes. The ash to be analyzed is placed in a hole 5 mm deep and 2.1 mm in diameter in the lower electrode; quartz ISP-22 or ISP-28 spectrograph is

used. Exposure of the plate to the flame of the arc should be during the first 2 minutes of combustion. The plates are of 2-40 H. and D. sensitivity, preferably positive. They are developed for 4.5 minutes in standard metol-hydroquinone developer at 16°C.

k) Visual interpretation of the spectrogram may be performed adequately by means of a MIR-12 or MIR-14 microscope, on the basis of analysis lines for gold: 2427.96Å; 2675.95Å; and 2748.3Å. Table 1, empirically arrived at,

TABLE 1. Data for calculation of gold content in terms of initial sample

Analysis lines of gold in spectral analysis of sorbent ash, Å			Gold content of initial sample, g/t
2427.96	2675.95	2748.3	
—	+	—	0.03
—	++	—	0.03-0.10
—	+++	—	0.10-0.15
+	+++	—	0.15-0.20
++	+++	—	0.20-0.25
+++	+++	—	0.25-0.30
+++	+++	+	0.30-0.60
+++	+++	++	0.60-1.5
+++	+++	+++	1.5

N. B. Key: (—) no line; (+) trace; (++) weak line; (+++) strong line.

is employed to calculate content in terms of the initial sample.

1) It must be emphasized that Table 1 can be used only under conditions of strict adherence to all listed conditions relative to the weight of the processed specimen, the calcining thereof, subsequent treatment with aqua regia, the specimen of sorbent, the type of sorbent, exposure time, current, film, development, interpretation, etc. Otherwise, it is necessary to make an advance analysis of standard samples of known content, from 0.03 to 2-3 g/t, in accordance with the method employed; and, to compile a table based on the results, employing that table thereafter.

It is recommended that standard specimens be prepared by the user, taking quartz as the base and introducing dissolved gold into the quartz specimen. The first, and most highly enriched, standard is prepared in this way. Subsequent standards are produced from this one by dilution with barren quartz. For sureness of results it is recommended that objective methods for determining the content, based on use of the photometer, be employed.

m) When a drum is employed for mechanical mixing in treatment of samples with aqua regia, analysis speeds attained in practice, come to 50 determinations per laboratory assistant per shift. Procedure for aurometric survey on the spot differs only in detail from any other metal-

lometric survey. Therefore, an aurometric survey as an entirety may and should be performed in accordance with the instructions on performance of metallometric studies compiled by A. P. Solovov [5]. One important detail in aurometric survey, however, is the fact that the sample should be taken from the humus horizon, at approximately 10-15 cm depth. The most highly enriched material is the < 1 mm fraction, and especially the < 0.1 mm fraction; therefore these classes should be used for analysis. In order to be sure of having 12.5 of < 0.1-1.0 mm fraction, initial weight of the field sample should be 200-300 g.

A field control of the preceding analysis was performed in 1956 by VITR, at a gold-ore deposit in the Baley district, eastern Transbaikalia; there, experimental studies of methods in an aurometric survey were conducted, based on the sample-analysis procedure described above. The result was discovery, near the veins, of gold dispersion halos not found by the usual spectral-analysis method in which concentration is not performed (fig. 1). Gold was found

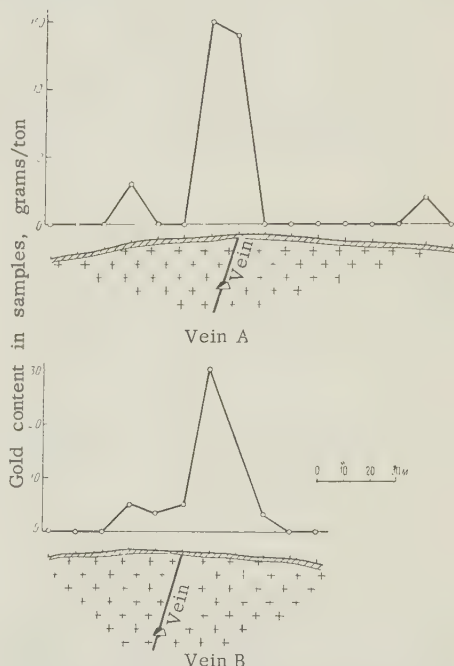


FIGURE 1. Results of aurometric survey along the dip of a vein. [hatched area] Eluvium and talus (1.5 meter thick); [plus signs] granites.

in the halos, starting at 0.05 g/t. At the same time, gold enrichment in the fine classes of sample material was proved; and, satisfactory identification of halos was performed, based on sampling of specimens from the humus horizon. Data obtained on the gold content of plants open perspectives for gold prospecting by tests of certain species; this matter, however, re-

quires further study. As a whole, results of the work provide every basis for belief that firm foundations have been established for introduction of aurometric survey into prospecting practice.

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# USE OF SURFACE FLOW OF SPRING WATER FOR HYDROCHEMICAL PROSPECTING OF ORE DEPOSITS<sup>1</sup>

by

S. R. Kraynov<sup>2</sup>

• translated by William Mandel •

## ABSTRACT

Small streams fed by subsurface run-off, subject to ore-oxidation activity, alter in chemical composition and are thus useful in hydrochemical prospecting for ores. Surface-flow types most favorable to hydrochemical prospecting are identified; and, the optimum time of the year established for positive identification of oxidizing-ore occurrences by surface-water chemical composition. The author chose the Lory plateau in Northern Armenia as the area of investigation. The topography of the area is mountainous; elevations above sea-level range from 1100 to 2700-2800 meters. Its climate is temperate alpine, and the annual precipitation of 650 to 750 millimeters is heaviest during the period from April to June. Sedimentary and effusive tuffs, of Middle Jurassic to middle Eocene age, contain numerous polymetallic, chalcopyrite, copper-arsenic, pyrite, and other ores; minerals are principally sulfides. A high-intensity water cycle resulting in abundance of springs and surface flows is characteristic of the region. For the regional run-off zones of underground flow, mineralization is as high as 500 milligrams per liter. Oxidizing ores affect chemical composition only of waters from the local run-off zone. The major-stream type of surface flow is more highly mineralized than the autonomous-stream type, and has greater discharge. Major-stream flow is subdivided into streams which collect their waters above local base level by discharging aquifers of the local run-off zone; and, streams of regional significance in which waters from the regional run-off zone are important. Changes in chemical composition are most significant in autonomous-stream types at low water level. Chemical composition of surface flow is influenced by oxidizing ores where stream waters originate above the local base level, but not where waters originate below base level. Degree of change in chemical composition of autonomous-stream waters depends upon mineralogical composition of ores. Change in chemical composition of major streams may attest to the presence of ore deposits; but it is a very poor indicator of mineralogical composition. The most definite identification of mineralized areas by surface water chemical composition occurs during low water. -- D. D. Fisher

The problem of changes occurring in chemical composition of surficial waters caused by oxidizing ores, was first posed by E. A. Sergeyev [3]; who investigated this problem in the Rudnyy Altay. The author, came to the conclusion that the decomposition of ore bodies results in enrichment of ore-oxidation products in surface flows, as revealed by chemical analysis.

A. A. Brodsky [1] notes from studies conducted at various ore deposits in the Soviet Union, that small streams fed by subsurface run-off subject ore-oxidation activity, undergo change in chemical composition and are useful therefore, to hydrochemical prospecting for ores.

In the course of hydrochemical studies in Northern Armenia (the Lory Plateau), we con-

ducted investigations for: 1) identification of the types of surface flow most favorable to hydrochemical prospecting; 2) determination of the best season for positive identification of oxidizing-ore occurrences by chemical composition of surface waters.

The topography of the district in which investigations were pursued, is mountainous. Altitudes above sea level are from 1100 to 2700-2800 m. The climate is temperate alpine with 650-750 mm annual precipitation, most abundant in the period from April to June.

Sedimentary and effusive tuffs from the Middle Jurassic to the Middle Eocene, containing numerous occurrences of polymetallic, chalcopyrite, pyrite, copper-arsenic and other ores, participate in the geological structure of the district. The ore minerals are principally sulfides. In most occurrences, the oxidation zone is weakly developed. An exception to this rule is provided by the chalcopyrite deposits, where the oxidation zone is quite distinct mineralogically. Supergene enrichment is not characteristic of all the occurrences. Hydrogeologically, the district is characterized by a high-intensity water cycle resulting in abundance of springs and surface flows.

<sup>1</sup>Translated from *Ispolzovaniye poverkhnostnykh potokov rodnikhovogo pitaniya pri gidrokhimicheskikh poiskakh mestorozhdeniy: Razvedka i Okhrana nedr*, no. 4, 1958

<sup>2</sup>VSEGINGEO

We distinguish the following depth zones of underground flow:

1. Local run-off zone. This is above the local base level; chemical composition of the waters is distinguished by negligible mineralization (not over 150 mg/L). The mineral content fluctuates within the following ranges:

Na+K	4-10 mg/L
Mg	0.4-6 mg/L
Ca	8-30 mg/L
Cl	3.7-5.4 mg/L
SO <sub>4</sub>	4.0-12.0 mg/L
HCO <sub>3</sub>	20-100.0 mg/L
Cu	none
Pb	none
pH	6.5-7.5

Within these limits, the content of these components vary with the nature of the aquifer.

2. Regional run-off zone. Below the former zone, but above the regional base level, which is the valley of one of the largest rivers, the Dzoraget, in this portion of Armenia. Mineralization of the waters is as high as 500 mg/liter.

Oxidizing ores affect chemical composition only of the waters in the local run-off zone. These changes depend upon mineralogical composition of ore occurrences; and, are expressed in an increase in sulfate ion and ore elements [2].

Surface currents of the territory under investigation have deep erosion valleys and flow at 1-3 m/sec [Tr.: 2.2 to 6.6 mph]. Flow at extreme low water varies between one liter and several cubic meters per second.

Surface streams arise as a result of combination of subsurface and surface run-off. Below, in Figure 1, we adduce a typical hydro-

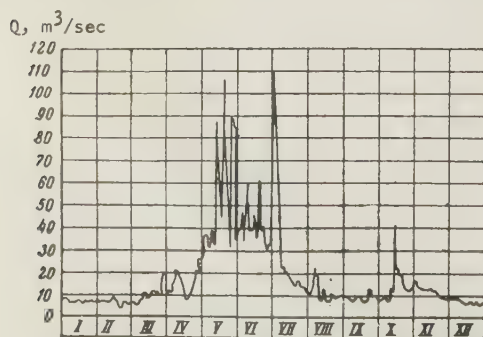


FIGURE 1. Hydrograph of the Dzoraget River.

graph of rivers on the plateau (data after V. P. Valesyan). The hydrograph shows subsurface feed to dominate for nine months of the year in

surface-stream formation; surficial run-off predominates for only three months. A two-year study of surface waters in the district enables us to distinguish two surface-flow types:

1. Autonomous: These flow and gather their waters on terrane composed of rocks from some single stratigraphic complex. Usually, these are short streams; their discharge does not, as a rule, exceed 10-100 L/sec. During low water these streams are fed by underground water from the local run-off zone.

During this period, chemical composition of autonomous-stream waters is analogous to that of groundwaters in the complex; and, completely reflects the laws of change therein.

2. Major waterways: These gather their waters from substantial basins composed of various rock assemblages. These streams have considerably greater discharge (up to several cubic meters per second; also, they reveal somewhat higher mineralization. Below we present a typical analysis of major stream waters:

Na+K	22.5 mg/L
Mg	9.5 mg/L
Ca	60.8 mg/L
Cl	10.7 mg/L
SO <sub>4</sub>	25.0 mg/L
HCO <sub>3</sub>	222.0 mg/L
pH	8.0

Major waterways are further classified as:

a) streams collecting their waters above local base level by discharging aquifers of the local run-off zone; and

b) streams of regional significance, in which waters from the regional run-off zone play a considerable role.

Investigations into the influence of oxidizing ores of varying mineralogical composition upon chemical activity proceeding in surface-stream waters of all these types, show the most significant changes in chemical composition to occur in waters of autonomous flows (sampled at low water).

Table 1 presents changes occurring in the chemical composition of waters from an au-

TABLE 1. An example of changes in chemical composition of autonomous stream waters as a result of their passage through an ore deposit.

Components	Content of components mg/L	
	Sampled above ore zone	Sampled 100 m downstream from ore zone
SO <sub>4</sub>	10.0	110
Cl	3.6	3.6
Cu	none	0.2

tonomous streams as the result of its passage through the ore zone of a chalcopyrite deposit; discharge fluctuates between 0.5 and 2-3 L/sec.

The influence of polymetallic and cuprohematic ores upon chemical composition of streams of the autonomous type is expressed only through increase in their relative sulfate content, determined by the  $\frac{SO_4}{Cl}$  ratio (fig. 2).

Figure 2 shows that oxidizing ores cause

The major regional streams, fed to a considerable degree by ground waters of the regional run-off zone, showed no change in chemical composition resulting from presence of ore deposits. The sulfate ratio for waters of these streams did not exceed a value of 2.0-2.5 in any case.

In order to determine the period when ore occurrences are most clearly defined by surface-water chemical composition, we determin-

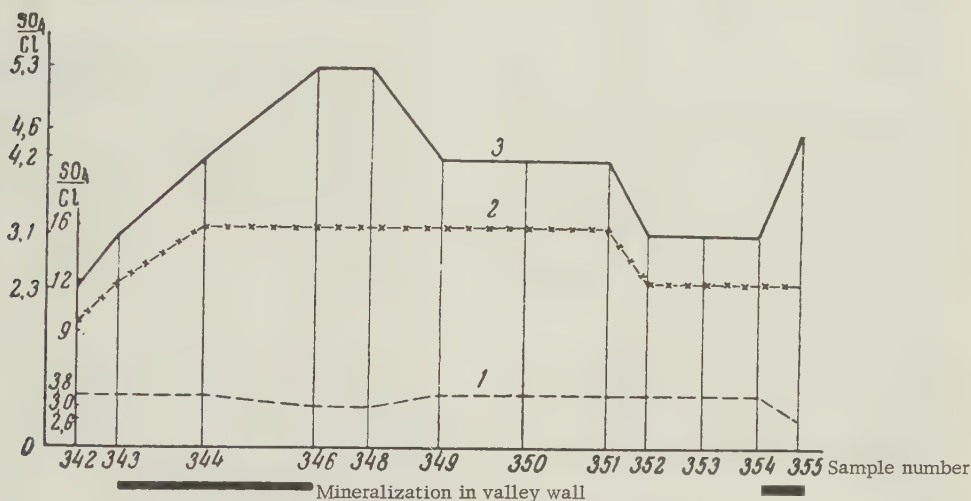


FIGURE 2. Change in  $\frac{SO_4}{Cl}$  ratio and in  $SO_4$  and  $Cl$  content along autonomous stream 1.

1) chlorine ion; 2) sulfate ion; 3)  $\frac{SO_4}{Cl}$  ratio

the value of the  $\frac{SO_4}{Cl}$  ratio to rise from 3 to 6. The halo of elevated sulfate content may be traced 500 m downstream from the oxidizing ore area. Chemical composition of the major stream waters varies in substantially lesser degree. These changes are expressed only by the increase in sulfate content (table 2).

ed the composition gradients for a number of autonomous streams intersecting ore zones.

The method of taking these seasonal gradients was as follows: a number of points corresponding to particular conditions of flow, at which monthly samples were taken, were se-

TABLE 2. Variation in chemical composition of major streams fed by underground waters of the local run-off zone

Components	Content of components mg/L				
	Stream 1	Stream 2	Stream 3	Stream 4	Stream 5
	No mineralization in basin		Polymetallic mineralization in basin	Cupro-arsenous deposit in basin	Chalcopyrite deposit in basin
$SO_4$	25.0	10.0	40.0	28.0	22.0
$Cl$	10.7	3.6	10.7	4.0	3.6
$\frac{SO_4}{Cl}$	2.5	2.7	3.7	7.0	6.1

As may be seen from Table 2, intensity of change in chemical composition of principal streams fed by underground waters (of the local run-off zone) is dependent only very slightly upon mineralogical composition of ores from the deposit.

lected in the channel. The samples were analyzed for  $SO_4$  and  $Cl$ . Data obtained from a seasonal-composition-gradient determination for one of the streams, are shown in Figure 3.

The first gradient, determined at the end of



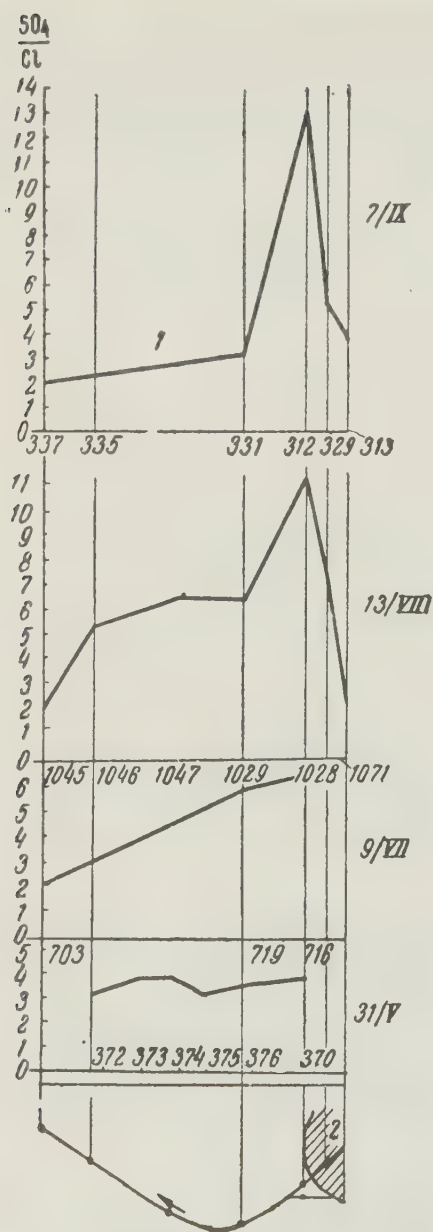


FIGURE 3. Time change in  $\frac{SO_4}{Cl}$  ratio along autonomous stream below mineralized sector.  
1) curve of  $\frac{SO_4}{Cl}$  ratio; 2) area of hydrothermally altered rocks with mineralization.

May when surface run-off predominated in feeding the stream, showed complete absence of any anomalies in chemical composition of the stream waters. Subsequently, diminution in the significance of surface feed and increase in that of underground supply at one of the sampling points, was reflected in a sulfate-ratio peak representative of mineralized rocks.

The peak appeared in July, increased steadily with time, and attained a maximum in September. The major conclusions to be drawn from this article are the following:

1. Influence of oxidizing ores is manifested in chemical composition of the waters of autonomous streams and of major streams which collect their waters above the local base level.

Chemical composition of the waters of major streams that gather their waters below the local base level, shows no change resulting from ore deposits.

2. Degree of change in chemical composition of autonomous-stream waters depends upon the mineralogical composition of the ore occurrences.

3. Change in chemical composition of major-stream waters may testify to the presence of ore deposits in their basins; but, is a very poor indicator of mineralogical composition.

4. The most definite identification of mineralized areas by surface-water chemical composition occurs during low water.

Be it noted that the foregoing conclusions are valid only for districts whose natural conditions are similar to those described (deeply intersected mountain districts with medium precipitation). In territories with different geographical conditions, the influence of oxidizing ores on surface-water chemical composition will doubtless manifest itself differently; this necessitates experimental investigations in typical districts.

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# Review Section

Sushkov, A. I., Troitsky, I. A., and M. A. Eydenzon, METALLURGY OF LIGHT METALS, CHAPTER 18, MAGNESIUM ORES, page 340. Extracted and translated by U. S. Joint Publications Research Service, JPRS/DC-L-1175.

Occurrences of magnesium in nature: According to academician A. E. Fersman the contents of magnesium in the earth's crust amounts to 2.35 percent. In nature, magnesium does not occur in free state, but occurs in the form of various compounds; most often, as silicate, carbonate, chlorides, and sulfates. Some magnesium minerals occurring in nature and their magnesium content are shown in Table 1.

The majority of the magnesium compounds enumerated are rock-forming minerals. A smaller number of them occurs in dissolved state in sea and salt-lake water, principally as chlorides and sulfates. About 3.7 percent of the total amount of magnesium in the earth's crust, occurs in sea water.

magnesite occurrence is a crystalline rock of white, grayish-white, and light bluish-gray color. Satka magnesite is distinguished by high magnesium-oxide content (44-46.9 percent) and by uniformity of its composition.

The largest occurrence of amorphous magnesite is the Khalilovo deposits in the region of Orsk-city in Chkalov oblast (43-47.7 percent MgO). High-grade magnesite deposits containing 45-46 percent MgO were discovered in Krasnoyarsk Kray along Rybnaya River. In the same region magnesite deposits containing 46.7 percent MgO were uncovered also in the basin of Udoroga River. Many other magnesite occurrences are known to exist in the U. S. S. R.

The largest and best explored dolomite occurrences in the U. S. S. R are: the Movotroitsk-Nikitovka, the Yelenov and Yamskoye (Donets Bassin), Shelkovskoye (Moscow oblast), Satka (Urals), Tzvarskoye (Leningrad oblast), etc. Dolomite contains 20-21 percent MgO. The Soviet Union holds first place in the world

TABLE 1\* Prevalent magnesium minerals

Name	Chemical formula	Magnesium content, weight percent
Magnesite	$MgCO_3$	28.8
Dolomite	$MgCO_3 \cdot CaCO_3$	13.2
Serpentine	$3MgO \cdot 2SiO_2 \cdot 2H_2O$	26.3
Olivine	$Mg_2SiO_4$	34.6
Bischofite	$MgCl_2 \cdot 6H_2O$	12.0
Carnallite	$MgCl_2KCl \cdot 6H_2O$	8.8
Kieserite	$MgSO_4 \cdot H_2O$	17.6

\*Table 21 of original text.

Characteristics of magnesium ores. Main occurrences of magnesium ores in the U. S. S. R.: The basic types of industrial raw materials for production of magnesium are: magnesite, dolomite, carnallite, as well as magnesium chloride contained in sea water and salt lake water.

The use of magnesium sulfates and silicates as raw materials to obtain magnesium is still in the experimentation stage.

The Soviet Union possesses large reserves of magnesite. The Satka magnesite occurrence in Chelyabinsk oblast is the largest deposit under exploitation in the U. S. S. R. The Satka

with respect to its magnesium and potassium salt reserves. The Verkhne Kamsk occurrence (Pern oblast) where the recovery and processing of magnesium and potassium salts is concentrated, is the main occurrence in the U. S. S. R. Carnallite occurs there in as several layers whose total thickness reaches 45 meters. The average chemical composition of Verkhne Kamsk industrial carnallite layers is as follows: 24 percent  $MgCl_2$ ; 19 percent KCl; 24.4 percent NaCl; 29.9 percent  $H_2O$ ; and the insoluble residue amounts to approximately 2.4 percent.

One of the characteristic peculiarities of that occurrence is the absence, or insignifi-

cance of sulfate content which considerably facilitates the processing of carnellite.

Other potassium-magnesium salt occurrences in the U. S. S. R. are represented by potassium and magnesium sulfates (Stebnik, Drogobych oblast, Ukrainian SSR), and as well by magnesium potassium-chloride sulfates (Kalush, Stanislav oblast Ukrainian SSR).

Besides the occurrences indicated, there is still a number of deposits containing magnesium salts (Inder salt occurrence, and salt deposits in the Volga-Emba region, Kazakh SSR), etc.

**Natural solutions of magnesium salts:** Sea water is the most prevalent source of dissolved magnesium salts. Magnesium content in sea water is comparatively low, and amounts to 3.8g  $MgCl_2$ , 1.7g  $MgSO_4$ , 0.1g  $MgBr_2$  [MgBr<sub>2</sub>?] per kg. of water.

Salt-lake water is a more concentrated solution of salts (including magnesium salts). There are many thousands of salt lakes in the U. S. S. R.; the Saki and Sasyk-Sinash salt lakes are in Crimea.

According to academician P. P. Budmikov, Sivash gulf in Azov Sea is an inexhaustible source of magnesium salts. About 30 million tons of sulfuric-acid and chloride salts of magnesium are contained at present in the waters of Sivash gulf.

Salt lakes of Volga-Emba region, Inder Lake (100 km<sup>2</sup>, Kazakhstan) Elton Lake (180 km<sup>2</sup>, Stalingrad oblast), are prospective industrial sources of magnesium raw material. The primary brine of these lakes contains 4-7 percent  $MgCl_2$  on the average.

Karabogaz-Gol Bay (magnesium chloride content in the brine amounts to 30 percent) is a powerful potential source for obtaining magnesium chloride.

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Kazanin, Yu. I., POLYMETALLIC MINERALIZATION OF THE NORTHEASTERN PART OF SOUTH ALTAY: *Izvestiya Akademii Nauk, Kazakh SSR, Seriya Geologicheskaya*, v. 30, no. 1, 1958, p. 47-51. Extracted and translated by U. S. Joint Publications Research Service, JPRS/DC-L-1155

In recent years, a new region of polymetallic mineralization has been exposed in the South Altay (Sarymsakty ridge). Six occurrences: Yuzhnoaltaysk, Nikitin Pnev, Kyzylsiir, Ushkungyy, Saralkarulak, and up to 200 ore manifestations have been uncovered, by the time of this writing, in the above mentioned region. These occurrences have been explored by a number of geologists.

According to their mineralogical composition, the following three main types of ore can be separated out:

1. The chalcopyrite-halenite\*sphalerite-pyritic type (at Nikitin occurrence) with a con-

siderable prevalence of pyrite, and of sphalerite in compact ores over halenite\* and chalcopyrite; their quantity, approximately, equal. The non-metallic minerals are: quartz, barite, sericite, less of chlorite, carbonate, alkite\* and adularia.

2. The sphalerite-halenitic type (at Yuzhnoaltaysk, Kyzylsiir, and Saralkarulak occurrences) with an insignificant quantity of pyrite and gray copper ores. The nonmetallic minerals are: carbonates, barite, quartz, in individual occurrences there are also: fluorite, alkite\*, and sericite.

3. The halessitic\* type (at Pnev and Ushkungyy occurrences) with a lesser quantity of sphalerite, pyrite, gray copper ores, etc. The nonmetallic minerals are: carbonates, barite, quartz, and, very seldom, sericite, and albite. The above enumerated peculiarities of polymetallic occurrences, ore fields, and ore manifestations of the Southern Ural, made it possible to draw the conclusion that this region represents a similar independent region, as the ore regions of Rudnyy Altay polymetallic belt (Leninogorsk, Sukyanovak, and others).

In the confines of the region under consideration, there are two occurrences which deserve to be first explored in detail. They are the Nikitin polymetallic, and the Yuzhnoaltay zinc-lead occurrences.

\*[Ed.: Mineral name not listed in Dana's manual of mineralogy, 17th ed., 1959.]

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OXIDATION-REDUCTION POTENTIAL METHOD OF EXPLORATION FOR PETROLEUM DEPOSITS: A review of Russian Literature, by George V. Chilingar, University of Southern California.

## ABSTRACT

The oxidation-reduction potential (ORP) method of exploration is based on the theory that those hydrocarbon gases that find their way into soil from the underlying oil-gas deposits, should reduce the oxidation-reduction potential of the soil. In addition, measured potentials are indicative of the oxidation or reduction state of ions present, and should be relatively low in the petroliferous areas because of the presence of strongly reduced petroleum substances.

In close proximity to the petroleum deposit, however, oxidation-reduction potential values are either abnormally low or high, or they exhibit sharp fluctuations which are hard to explain in some cases. Possibly, the presence of some oxidizing compounds associated with petroleum deposits could account for some abnormally high values.



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Notwithstanding its many shortcomings, the ORP method can be used in conjunction with other geochemical exploration methods. --Auth.

### INTRODUCTION

The pH and  $E_h$  values for different types of rocks apparently reflect their chemical-mineralogical composition (fig. 1). These results

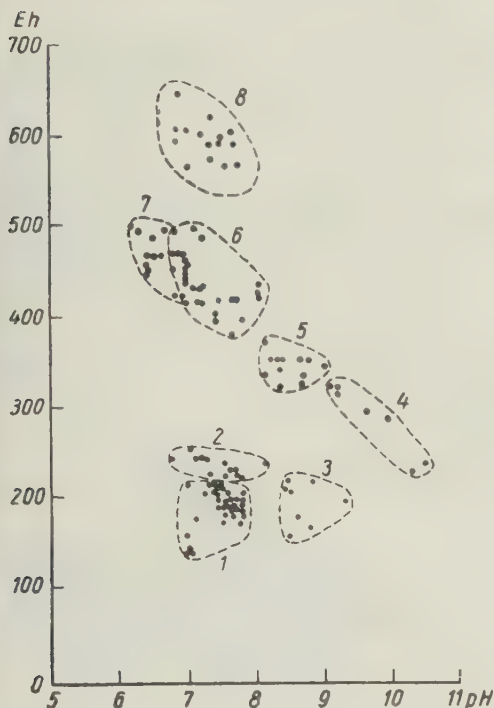
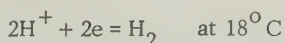


FIGURE 1. Physical-chemical characteristics of some sedimentary rocks. 1) siderites, very slightly affected by the oxidation processes; 2) siderites affected by the oxidation processes; 3) siderites with calcium carbonate admixture; 4) limestones; 5) calcareous clays (1 through 5 are from Berezov deposit of Chitin area); 6) limonites (Berezov deposit from Chitin area and Kireev ore of Tula area); 7) clays devoid of carbonates (Berezov deposit of Chitin area); 8) Iron-manganese ores (Botom deposit of Yakutia).

reported by Strakhov et al [18, p. 124] differ slightly from those reported by Krumbein and Garrels [8].

The  $rH_2$  values can be calculated for a given medium on taking: 1) an  $E_h$  reading and 2) a pH reading. The calculation is based on the fact that, on the hydrogen electrode scale,  $E_h$  for the reaction



is given by the equation

$$E_h = 0.029 \log \frac{[H^+]}{[H_2]}$$

because  $E_h^0$  for this reaction is arbitrarily taken as zero. Thus,  $rH_2$  for a medium is given by the formula

$$rH_2 = -\log [H_2] = \frac{E_h}{0.029} + 2pH$$

The negative logarithm of molecular hydrogen concentration is called  $rH$  in U. S., presumably because it was so called by its originator W. Mansfield Clark [2].

The  $E_h$  values are higher in a more oxidized medium; and a medium with higher  $E_h$  would oxidize a medium with lower  $E_h$ . Kartsev et al [6] state that  $rH_2$  values are higher in a more oxidized medium. Examination of the above equation, however, reveals that as the  $E_h$  increases the  $rH_2$  increase constitutes only 3.44 percent of the  $E_h$  difference; if the pH decreases, the  $rH_2$  goes down by twice the number of units. Hence the  $rH_2$  may either go up or down with increased oxidation, depending on the concomitant pH changes. A comprehensive review of the methods of determining pH and  $E_h$  values for sedimentary rocks was presented by Strakhov et al [18, p. 116-127].

According to Kartsev et al, inasmuch as the hydrocarbons are relatively reduced compounds, their presence would result in lower  $E_h$  readings. If the gaseous hydrocarbons were oxidized by the soil constituents, the latter would be left in a reduced state which will be recorded by the potential measurements. Although the hydrocarbons do not ionize, it should be remembered that some reducing compounds are commonly associated with hydrocarbons. In this connection, it should be mentioned that  $H_2S$  poisons the electrodes and causes them to read differently.

### OXIDATION-REDUCTION POTENTIAL (ORP) METHOD AS USED BY V. E. LEVENSON

The oxidation-reduction potential method of exploration for petroleum (ORP method) was first used by Levenson [9] in 1935. His method involves the determination of the electrical potential which develops between the electrode and the surrounding medium, namely rocks, soil, and water. Levenson believed that the measured potentials are indicative of the nature of ions present and the ratio of oxidized to reduced ions, and that in most cases they should be relatively low in petroliferous areas because of the presence of strongly reduced petroleum substances.

Levenson and his collaborators determined

the  $E_h$  values of samples obtained from definite horizons in the prospecting pits and bore holes. These determinations were made with a potentiometer in the potassium-chloride extracts from rock samples, saturated with  $CO_2$  (fig. 2).

void of petroleum bitumens, have even lower  $E_h$  and  $rH_2$  values than the petroliferous rocks which do not contain  $H_2S$ , because  $H_2S$  is a stronger reducing agent than are hydrocarbons.  $H_2S$  by itself, however, may be an indirect

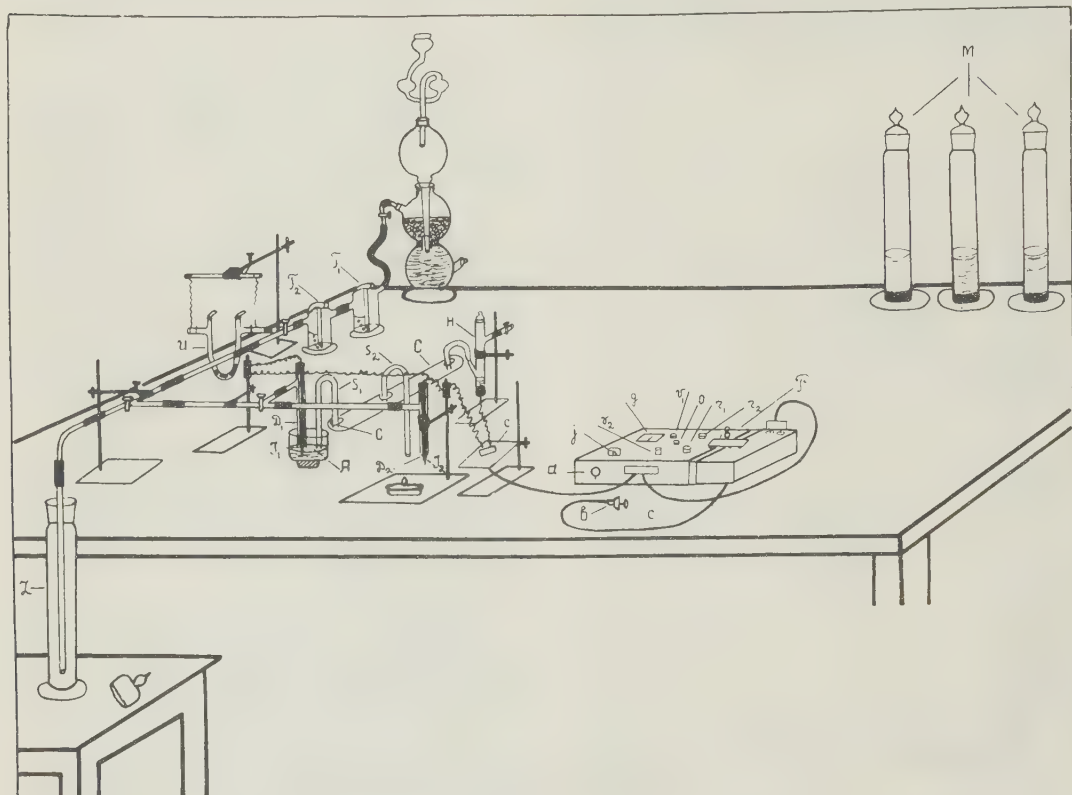


FIGURE 2. Levenson's apparatus for measuring  $rH$  in field laboratory (Levenson, 1939)  
A) container with sample;  $D_1$ ,  $D_2$ ) tubes supplying  $CO_2$ ;  $J_1$ ) electrode for determining  $E_1$ ;  $J_2$ ) electrode for determining  $E_{Cl}$ , the latter two electrodes pass through  $D_1$  and  $D_2$ ;  $S_1$ ) agar siphon for determining  $E_1$ ;  $S_2$ ) agar siphon for determining  $E_{Cl}$ ; C) electrolytic connection; H) calomel electrode; P) potentiometer;  $r_1$ ,  $r_2$ ) graduated round rheostats;  $v_1$ ,  $v_2$ ) runners; o) pole-changing switch; g) galvanometer; j) corrector for galvanometer; a) stopping device; c) binary connection; K) Klipp generator (supply of  $CO_2$ );  $T_1$ )  $CuSO_4$  solution;  $T_2$ ) distilled water; u) tube with iodine-starch paper; z) cylinder for  $CO_2$  accumulation; and M) cylinders after shaking samples with KCl solution.

In several instances they found that the values of  $E_h$  and  $rH_2$  decreased on approaching petroliferous areas. For example, this method was successfully used in the Troekurovo-Gubinskaya area as reported by Fedorov [3].

Some difficulties, however, were encountered in interpreting the  $E_h$  and  $rH_2$  values. According to Kartsev et al [6, p. 369], it was established that the rocks containing  $H_2S$ , but de-

indicator for the presence of petroleum.

According to Kartsev et al [6, p. 369], it was established also that the presence of only solid petroleum bitumens or heavy oil often does not affect appreciably the  $E_h$  values.  $E_h$  values are not affected appreciably even in close proximity to some small heavy-oil deposits, such as those at Shubany, U. S. S. R. Possibly this is a result of absence of lighter

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gaseous hydrocarbons in the soil. Kartsev et al, however, point out that notwithstanding the shortcomings previously discussed, the ORP method as developed by Levenson deserves considerable attention; at the present time, further research and testing are being conducted in order to improve his method.

### OXIDATION-REDUCTION POTENTIAL METHOD DEVELOPED BY I. P. SERDOBOLSKY

Serdobolsky [12] and his coworkers developed another ORP method, involving survey of the oxidation-reduction potential of soils. His method is based on the theory that the hydrocarbon gases that find their way into the soil from the underlying oil-gas deposit, should reduce the oxidation-reduction potential of the soil. Thus, information obtained by this method should, in general, be equally as useful as that obtained by the "gaseous survey of soil" method (analysis of subsoil air for hydrocarbon content). Yasenev [22] cites many examples (such as fig. 3) which show the validity of the latter method.

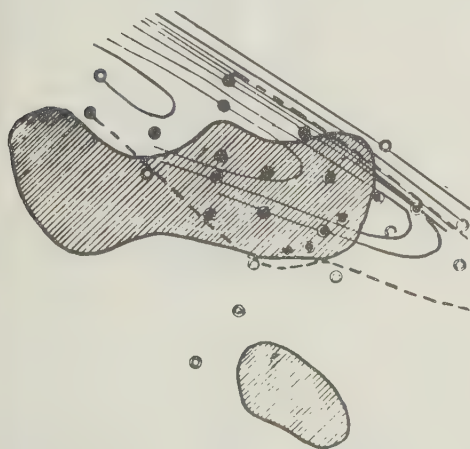



FIGURE 3. Gaseous anomaly over one of the oil-fields of Kuban (USSR), after Yasenev, 1956. — structural contours on top of second horizon of Middle Maykop formation,  gaseous anomaly; --- productive limits; ● deep bore holes; and ○ bore holes which produced oil.

The Serdobolsky ORP method was tried in several petroliferous areas of Transcaucasia and other regions of U. S. S. R. The oxidation-reduction potential measurements were made directly in the soil (in pit walls up to 50 cm depth) using a potentiometer with condenser. This investigation was conducted in conjunction with the salts-in-soil and bitumens-in-soil

surveys, described by Kartsev et al [6]. The existence of negative ORP anomalies for soils, apparently resulting from influence of oil-gas deposits, were established. Figure 4 shows a transverse profile of ORP values for soil (in mv) in one of the petroliferous areas investigated by Serdobolsky [12].

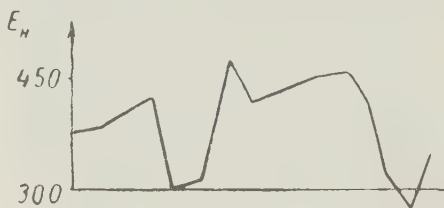


FIGURE 4. Transverse profile of oxidation-reduction potential of soil (in mv), after Serdobolsky, 1948. Apparently distance along the traverse is plotted on the abscissa (scale not given).

On conducting investigation in some of the petroliferous areas of U. S. S. R., Serdobolsky [12] discovered that one hour after removing the samples from the ground the ORP values increased by 80-120 mv. This constitutes one of the reasons why he recommended that ORP measurements should be made directly in the field.

### LABORATORY VERSUS FIELD DETERMINATIONS OF OXIDATION-REDUCTION POTENTIAL OF SOILS

Slavin [16] discussed the advantages and disadvantages of measuring ORP of soil samples in the laboratory as compared to field measurements. In most cases, the ORP values change after removal of samples from the ground. This change depends on the physical, chemical, and biological attributes of the samples and on the geological and general physico-geographical characteristics of the investigated area.

Slavin [16, p. 105] found that in some cases results obtained in the laboratory and in the field give a similar overall picture, whereas in other cases the laboratory and field data differ considerably.

According to Slavin [16, p. 106], values of ORP measured in the lower horizons of one prospecting pit 16 hours after the excavation, were 50-100 mv higher than those measured originally. This was probably a result of considerable change in degree of aeration of lower horizons of the prospecting pit upon excavation. Prior to excavation, the degree of aeration was lower because of a tight cover of plant and grass roots. In addition, in this area there



was possibly a very slow diffusion of components from the petroleum deposit.

In another area, Slavin [16, p. 105] discovered that successive ORP determinations in the field were practically the same for 2-3 months with uniform weather. Rains resulted in lowering of the potential by 100-300 mv; however, a few days after the rain, ORP values were as high as before. The constancy of ORP values in this case possibly can be explained by continuous influx of geochemical agents from the petroleum deposit [Slavin 16, p. 105]. On the other hand, rain has very small effect on potential of some chernozem soils [Slavin 16, p. 106].

As Slavin [16, p. 104] pointed out, advantages of laboratory determinations for ORP include (1) higher accuracy, (2) greater speed, and (3) more uniform environment of testing.

#### CHANGE IN ORP WITH SOIL CHARACTERISTICS AND DEPTH

The value of oxidation-reduction potential for soil varies widely with moisture and humus content, soil inhabitants, degree of aeration, and other factors. Because of the morphological soil heterogeneity, resulting from the soil processes such as gleying, the oxidation-reduction potential determined in the same pros-

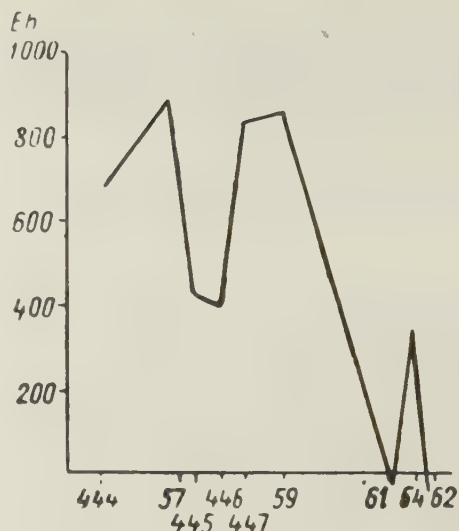


FIGURE 5. Lowering of oxidation-reduction potential (pits 61, 62, 64) due to the soil-geomorphological conditions (after Slavin, 1954).

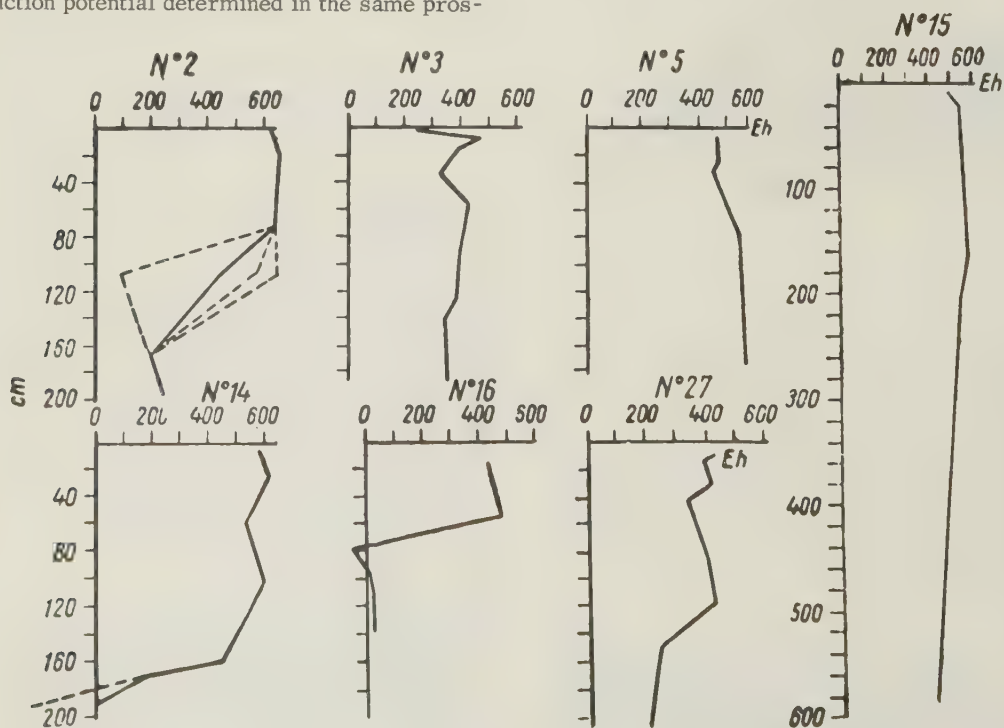


FIGURE 6. Examples of variation of oxidation-reduction potential with depth (after Slavin). Depth from the surface in cm is plotted on the ordinate, whereas  $E_h$  in mv is plotted on the abscissa.

## REVIEW SECTION

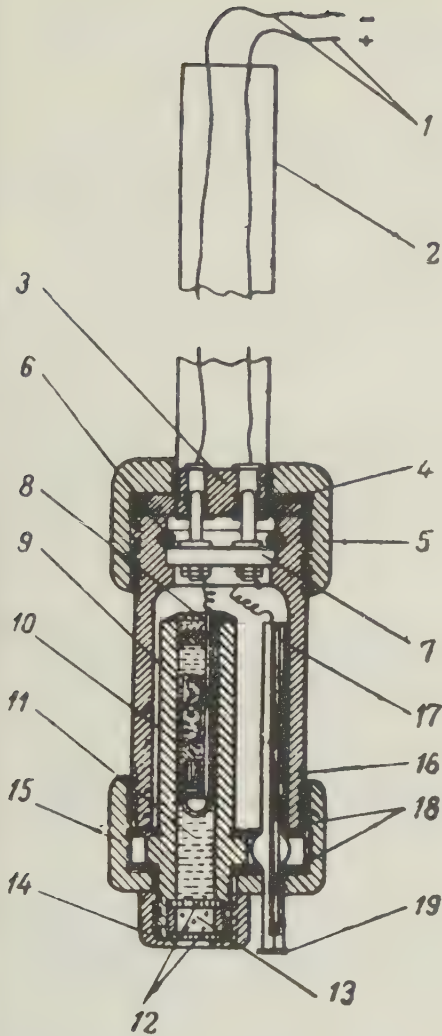


FIGURE 7. Vaynbaum's equipment for  $rH$  determinations (Vaynbaum, 1953). 1) wiring; 2) Duralium tube; 3) socket; 4) supporting ring; 5) upper nut; 6) check ring; 7) crotch; 8) Mendeleyev's paste; 9) ebonite tube of half-cell; 10) calomel half-cell; 11) saturated KCl solution; 12) porous partitions; 13) agar-agar mass with KCl solution; 14) nut of the tube; 15) lower nut; 16) ebonite housing; 17) electrode tube; 18) rubber packing; and 19) platinum electrode.

pecting pit and at the same depth could vary by as much as 200-500 mv (and higher) [Slavin 16, p. 107].

Local changes of potential resulting from surface factors (soil-forming processes) should be considered in order to avoid er-

roneous conclusions. For example, Figure 5 shows low  $E_H$  values for pits 61, 62, and 64, which are located on a young marine terrace with swampy soils.

ORP values measured at the same depth could vary by as much as 100 mv (and higher) because of geochemical heterogeneity of the soil Slavin [16, p. 108].

As shown in Figure 6, potential can vary with depth; in most cases it decreases with depth. In some instances there is gradual reduction in potential with depth (section 15, fig. 6); whereas in other cases, there is either a sharp reduction in potential from a certain depth or fluctuation of higher and lower values. Slavin [16, p. 109] observed sharp reductions in potential in gleyed soil horizons. It is imperative, therefore, that the potential measurements in different prospecting pits should be made at a definite genetic horizon and not at a definite depth.

In order to minimize the effect of surface factors, Vaynbaum [19, 20] proposed an underground ORP survey at a depth of not less than 2-3 m (in walls of prospecting pits) with an aid of special equipment (fig. 7). Such surveys were conducted in the Middle Along-Volga region. Slavin [16, p. 109], however, found that even slight variations in soil-forming processes affect readings of potential to a depth of 6-8 m (and deeper).

### JOINT UTILIZATION OF SEVERAL METHODS OF EXPLORATION FOR PETROLEUM IN MIDDLE ALONG-VOLGA REGION

For three years (1947-1949), Lobov [11] studied six different areas in Middle Along-Volga region by using three different methods of geochemical exploration for petroleum. He would obtain one gas sample and two formation samples from 2- to 3-m deep bore holes. One formation sample was used for ORP determinations; the other, for the luminescent-bituminologic examination.

In most cases, zones having minimum  $rH_2$  values were closely linked with other geochemical anomalies (fig. 8). The  $rH_2$  values of the anomalous area were 2-3 units lower than those of surrounding areas. Lack of superposition or overlapping of different geochemical anomalies can possibly be explained by peculiarities of the local tectonic movements which change the direction and intensity of hydrocarbon migration. On the basis of his findings, Lobov [11] recommended drilling in several of the areas investigated (including those shown in fig. 8). Results of drilling, however, have not been reported by Lobov [11].

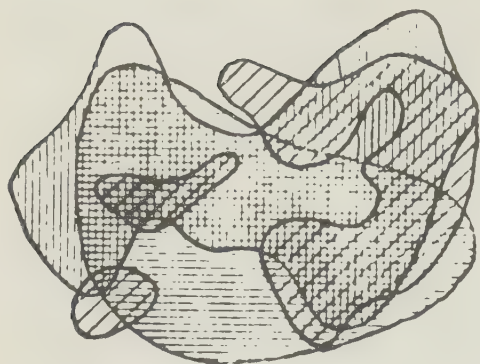


FIGURE 8. Results of geochemical methods of exploration for petroleum in two areas of Middle Along-Volga region (after Lobov, 1953). gaseous survey; luminescent-bituminologic method, and ORP method.

#### POSITIVE AND FLUCTUATING ORP ANOMALIES

Serdobolsky [12] and Slavin [16] observed that in some cases instead of reduction there is an increase or sharp fluctuations of the oxidation-reduction potential in petroliferous areas (fig. 9). According to Slavin [15], the anomalous increase in ORP values over gas-oil deposits possibly results from influence of such elements as iodine and bromine, which are associated with petroleum deposits. Possibly, these elements oxidize the soil.

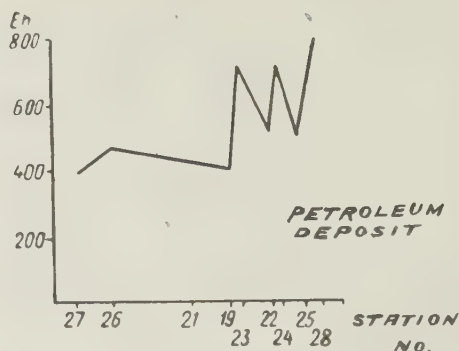


FIGURE 9. Example of variation in oxidation-reduction potential of ground (in mv) on approaching a petroleum deposit (after Slavin, 1954). Distance between stations is not given.

#### CONCLUSIONS

ORP values of ground in petroliferous areas could be either abnormally low or high, or could exhibit sharp fluctuations. On interpreting ORP values, one should consider: 1) soil characteristics; 2) sampling techniques and effects of moisture, degree of aeration and temperature; and 3) geological and general physicogeographical characteristics of the area investigated.

On the basis of some experimental work, not released for publication at the present time, the reviewer believes that it is preferable to measure ORP directly in the field at a depth of not less than 2-3 m. The measurements in different prospecting pits should be made at a definite genetic horizon and not at a definite depth. The reviewer also found that soil has to contain sufficient moisture for reliable ORP measurements in situ.

It seems, that at the present stage of its development, the ORP method can be used only in conjunction with other exploration methods. Further research work is necessary for improving this method.

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